INTERACTION OF HUMIDITY AND AIR POLLUTANTS ON VEGETATION

Final Report

Prepared for the California Air Resources Board

for Contract No. A5-160-33

July 16, 1986 - April 30, 1988

C. R. Thompson, Principal Investigator

David M. Olszyk, Co-Principal Investigator

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ABSTRACT

The primary objective of this study was to determine the extent to which relative humidity affects plant responses to air pollutants in the field. This objective was addressed using a unique field humidification system which adds dry steam to large open-top chambers on the campus of the University of California at Riverside. The system was expanded to supply humidity to a total of six chambers. The objective was addressed in three sequential studies evaluating: the response of plants to ambient ozone and/or added humidity in the late summer and early fall of 1986; the response of five winter crops exposed to sulfur dioxide and/or added humidity in the winter of 1986-87; and the response of five tree and herbaceous species exposed to ambient ozone and/or added humidity in the spring and summer of 1987.

In the fall oxidant x humidity study there were five treatments: ambient air (high ozone) and ambient (dry) humidity, ambient air and added (35% above ambient between 1100 and 1600) humidity, filtered (low ozone) and ambient humidity, filtered air and added humidity and outside check plots. The study used tomatoes (Lycopersicon esculentum).

In the winter sulfur dioxide x humidity study there were five treatments: ambient air (no sulfur dioxide) and ambient (dry) humidity, ambient air and added (40% above ambient between 1100 and 1600) humidity, ambient air plus 0.12 ppm sulfur dioxide) and ambient humidity, 0.12 ppm sulfur dioxide and added humidity, and outside check plots. The study used wheat (Triticum aestivum), lettuce (Lactuca sativa), carrots (Daucus carota), and onions (Allium cepa).

In the spring oxidant x humidity study there were five treatments: ambient air (high ozone) and ambient (dry) humidity, ambient air and added (25% above ambient between 1100 and 1600) humidity, filtered (low ozone) and ambient humidity, filtered air and added humidity and outside check plots. The study used beans (Phaseolus vulgaris), melons (Cucumis melo), almonds (Prunus dulcis), ponderosa pine (Pinus ponderosa), and Douglas fir (Pseudotsuga menziesii).

Overall this study indicated that there is a definite interaction between humidity and air pollution on leaf injury, with increasing humidity greatly increasing the amount of visible leaf necrosis and senescence

from ozone. However, this injury interaction was not associated with any general interaction in terms of crop yield. There were a few statistically significant humidity x air pollutant interactions for growth and biomass production of plants, with increased ozone effect in humid chambers in the Spring ozone study and decreased sulfur dioxide effect in the Winter study.

Ozone alone caused visible injury to tomatoes, almonds, beans, and melons. It also resulted in significant reduction in yield, growth, and biomass production for tomatoes and beans, and reductions in physiological processes (stomatal conductance, photosynthesis, and transpiration) for tomatoes, beans, and almonds. Sulfur dioxide by itself reduced growth and biomass production for wheat and lettuce, and yield (weight/ear) for wheat. Humidity, in general, increased plant growth and biomass production for tomatoes, carrots, onions, lettuce, and beans. Added humidity resulted in increased yield for carrots, onions, and lettuce, but decreased yield in beans and possibly tomatoes. Humidification also resulted in increases in physiological process rates for tomatoes, wheat, lettuce, onions, almonds, and beans.

Overall, this study indicated that there is no general synergism resulting in greater yield losses from air pollutants for plants exposed at higher humidity levels. In fact for wheat and lettuce, sulfur dioxide reduced yields more in dry chambers compared to humid chambers. Evidently, the increase in stomatal conductance indicates the potential for greater pollutant effects at higher humidities, but the plant's greater growth in humid air compensates for these effects.

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DISCLAIMER

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SUMMARY AND CONCLUSIONS

Relative humidity, i.e., the water vapor content of air, has long been considered to be an important factor in the determination of air pollutant sensitivity of plants. In general, stomata of plants are more open when grown under conditions of high compared to low humidity. Open stomata allow an increase in the amount of air pollutants taken up by the leaves, thus increasing the amounts of toxic pollutant metabolites at the cellular level. At low humidities a relatively greater amount of water is lost from leaves via transpiration than at high humidities, thus limiting pollutant uptake by inhibiting the mass flow of pollutants into leaves and adsorption of pollutants to leaf cells. The cumulative effect of these metabolic changes is a large (50-100%) decrease in leaf injury with a decrease in humidity from ~80-30%.

Humidity has been suggested as one of the most important factors determining the relative pollutant sensitivity of crops growing in different climatic areas of the country. It was hypothesized that different regional air quality standards may be designed to protect vegetation considering variations in regional environmental conditions, especially in regard to humidity. Such standards would likely allow higher pollutant concentrations in low humidity areas such as the southwestern United States than in high humidity areas such as the humid East.

However, not all variation in humidity is national in scope. Differences in humidity can occur between geographical areas of a state such as the Central Valley vs. the South Coast Air Basin of California or between coastal areas and inland desert areas. Differences in humidity can also be seasonal such as early spring vs. summer or fall. For example, coastal areas such as the Oxnard area have a higher relative humidity level than Central Valley or southern inland areas throughout the year. In addition, coastal areas have a relatively uniform humidity level throughout the day, while Central Valley areas have a higher humidity level in mornings than afternoons during all parts of the year.

Unfortunately, all conclusions concerning humidity x air pollutant reactions to date have been based on experiments conducted in controlled environments or greenhouse studies; no field studies investigating humidity and air pollutants have been carried out. Thus, the predicted

importance of humidity in crop sensitivity to pollutants was approached with caution and has not been of great use for air management decisions.

A major contributing factor for the lack of field studies of humidity x air pollutant interactions was the lack of a humidification system suitable for open-top chambers or other field exposure systems. Field projects to date concentrated on yield responses to different air pollutant concentrations, with essentially no effort being made to evaluate modifications in the exposure system appropriate for controlling humidity.

A field humidification system was developed previously for use with open-top field chambers at the University of California, Riverside. The humidification system consisted of an extended length blower box, humidifier-humidstat system including modulating valve, steam lines, steam boiler and heated water reservoir, water softener, and propane fuel tank. The system was tested extensively over a wide range of relative humidities. There was little excess heating of the air and little reduction of the air pollutant level in the chamber when the steam was injected. No liquid water entered the chamber. The system was documented in terms of propane, water, and power use for humidification, and construction costs for humidification per chamber were determined.

The humidification system was controlled manually, because relative humidities in ambient air in Riverside were found to be very uniform during daylight hours, varying less than 10% over the day under most conditions. Thus, the system worked well to provide a constant addition of humidification of from 20-60% above ambient with only manual controls.

The primary objective of the current study was to determine the extent to which relative humidity affects plant responses to air pollutants in the field. This objective was addressed using the unique field humidification system and expanded to supply humidity to a total of six chambers. The objective was addressed in three sequential studies evaluating (1) the response of plants to ambient ozone and/or added humidity in the late summer and early fall of 1986; (2) the response of four winter crops exposed to sulfur dioxide and/or added humidity in the winter of 1986-87; and (3) the response of five tree and herbaceous species exposed to ambient ozone and/or added humidity in the spring and summer of 1987.

In the Fall oxidant x humidity study, there were five treatments: ambient air (high ozone) and ambient (dry) humidity, ambient air and added

humidity (30% above ambient between 1100 and 1500), filtered (low ozone) and ambient humidity, filtered air and added humidity, plus outside check plots. The study used tomatoes (Lycopersicon esculentum).

In the Winter sulfur dioxide x humidity study, there were five treatments: ambient air (no sulfur dioxide) and ambient (dry) humidity, ambient air and added humidity (35% above ambient between 1000 and 1500), ambient air (plus 0.12 ppm sulfur dioxide) and ambient humidity, 0.12 ppm sulfur dioxide and added humidity, plus outside check plots. The study used wheat (Triticum aestivum), lettuce (Lactuca sativa), carrots (Daucus carota), and onions (Allium cepa).

In the Spring oxidant x humidity study, there were five treatments: ambient air (high ozone) and ambient (dry) humidity, ambient air and added humidity (25% above ambient between 1000 and 1500), filtered (low ozone) and ambient humidity, filtered air and added humidity, plus outside check plots. The study used beans (Phaseolus vulgaris), melons (Cucumis melo), almonds (Prunus dulcis), ponderosa pine (Pinus ponderosa), and Douglas fir (Pseudotsuga menziesii).

Overall, this study indicated that there is a definite interaction between humidity and air pollution on leaf injury, with increasing humidity greatly increasing the amount of visible leaf necrosis and senescence from ozone as shown in previous studies. However, contrary to expectations, leaf injury was not generally associated with reduced crop yield. This may be at least partially due to the fact that injury is somewhat subjective as it is based on a measurement of early leaf drop and, thus, may be only qualitatively related to yield. There were a few significant (note: significance refers to statistical significance of at least $p < 0.05$), humidity x air pollutant interactions for growth and biomass production of plants. For example, there was increased ozone effect in humid chambers in the Spring ozone study, and a decreased sulfur dioxide effect in the Winter study.

Ozone by itself caused visible injury to tomatoes, almonds, beans, and melons as observed previously for most of these species. It also resulted in significant reductions in yield, growth, and biomass production for tomatoes and beans, and reductions in physiological processes (stomatal conductance, photosynthesis, and transpiration) for tomatoes, beans, and almonds. Sulfur dioxide alone reduced growth and biomass

production for wheat and lettuce, and yield (weight/ear) for wheat. Humidity, in general, increased plant growth and biomass production for tomatoes, carrots, onions, lettuce, and beans. Added humidity resulted in increased yield for carrots, onions, and lettuce, but decreased yield in beans and possibly tomatoes (because the tomatoes were planted late in the season, they were harvested unripe and before the maturity needed for actual economic yield). Humidification also resulted in increases in physiological process rates for tomatoes, wheat, lettuce, onions, almonds, and beans.

Overall this study indicated that there is no general synergism resulting in greater yield losses from air pollutants for plants exposed at higher humidity levels. Evidently, the increase in stomatal conductance indicates the potential for greater pollutant effects at higher humidities, but the greater growth of plants in humid air compensates for these effects.

Conclusions

(1) Increased relative humidity resulted in a synergistic (greater than additive) increase in leaf injury from ozone compared to drier (ambient) humidity conditions. This occurred for all species which were relatively sensitive to ozone, including tomatoes, beans, melons, and almonds.

(2) Increased relative humidity was not associated with any interactive effect on the amount of yield loss due to ozone, i.e., the percentage yield loss for humdified/ambient ozone plants was the same as the additive effects of humidity or ozone alone.

(3) The increased ozone injury with added humidity was associated with increased stomatal conductance and transpiration.

(4) The results with sulfur dioxide were somewhat different from those with ambient ozone. There was a significant humidity x sulfur dioxide interaction for all parameters of lettuce and for wheat weight/ear. The effects of sulfur dioxide were actually greater in the dry than humid treatment for these parameters. This effect may be associated with a slightly lower sulfur dioxide content in the humid chamber, but the decreased sulfur dioxide sensitivity in humid air also may be real.

(5) Future humidity x ozone studies should focus on establishing multiple (at least three) levels each of humidity and ozone in order to produce response surfaces. This would be difficult and may involve limited replication of each chamber and careful experimental design.

RECOMMENDATIONS

(1) The humidity studies conducted to date have focused on design, testing, and operation of the expanded humidity system, and general responses of a variety of crops to humidity and air pollution using a simple statistical design: two levels of humidity x two levels of pollutant. Future studies should focus on a more complex experimental design with one species to produce a multivariate humidity and pollutant dose x plant response surface. This experimental design should somehow incorporate at least three levels each of humidity and pollutant.

(2) The experiments should focus on ozone; sulfur dioxide is not currently as important a pollutant problem. Sulfur dioxide produced a few responses, but at unrealistically high concentrations.

(3) The experiments should focus on an in-depth analysis of growth development and yield, with multiple harvests to indicate how humidity and ozone affect plants.

I. INTRODUCTION

Relative humidity, i.e., the water vapor content of air, has long been considered to be an important factor in the determination of air pollutant sensitivity of plants. In general, stomata of plants are more open when grown under conditions of high, compared to low, humidity (4,8,9,11,17,18). At high humidities, open stomata allow an increase in the amount of air pollutants taken up by the leaves, thus increasing the amounts of toxic pollutant metabolites at the cellular level (8-11). At low humidities, stomata tend to close, thus reducing pollutant uptake. In addition, at low humidities a relatively greater amount of water is lost from leaves via transpiration than at high humidities because of the greater pressure differential for water vapor between the leaf and air. The increased transpiration may limit pollutant uptake by inhibiting the mass flow of pollutants into leaves and adsorption of pollutants to leaf cells (1). The cumulative effect of these metabolic changes is a large decrease (50-100%) in leaf injury with a decrease in humidity from ~80-30% [with a day temperature of 27°C and a night temperature of 21°C (4)].

Humidity has been suggested as one of the most important factors determining the relative pollutant sensitivity of crops growing in different climatic areas of the country. McLaughlin and Taylor (10) hypothesized that different regional air quality standards may be designed to protect vegetation, considering variations in regional environmental conditions, especially with regard to humidity. Such standards would likely allow higher pollutant concentrations in low humidity areas, such as the southwestern United States, than in high humidity areas, such as the humid East.

However, not all variation in humidity is national in scope. Differences in humidity can occur between geographical areas of a state, such as the Central Valley vs. the South Coast Air Basin of California (5) or between coastal areas and inland desert areas. Differences in humidity can also be seasonal, such as early spring vs. summer or fall. For example, coastal areas, such as the Oxnard area, have higher relative humidity levels throughout the year than do Central Valley or southern inland areas. In addition, coastal areas have relatively uniform humidity levels throughout the day, while Central Valley areas have higher humidity levels in mornings than in afternoons during all parts of the year.

Humidity differences also occur on a local level, especially between fields with a dense canopy of crop foliage vs. dry open areas. Standing water such as following furrow irrigation episodes also can have a dramatic effect on localized humidity, especially when seedling plants allow for large areas of exposed soil. Under these conditions, newly irrigated fields can become large evaporative surfaces causing locally high humidity levels. This could dramatically affect the air pollutant sensitivity of the seedlings at a time when pollutants could have a critical effect on crop establishment and important early growth. In 1983 an ozone episode in Orange County, CA had a devastating effect on dry bean cultivars the day after a furrow irrigation (7). Earlier ozone episodes, when the soil was dry, did not have such a severe effect on the plants even though the ozone concentrations were high. While relative humidity was not measured during this study, an increased humidity associated with furrow irrigation is a possible cause of the increased plant sensitivity to ozone.

Unfortunately, all conclusions concerning humidity x air pollutant reactions to date have been based on experiments conducted in controlled environments or greenhouse studies; no field studies investigating humidity and air pollutants have been carried out. Thus, the predicted importance of humidity in crop sensitivity to pollutants has been approached with caution, and has not been of great use for air management decisions.

A major contributing factor for the lack of field studies of humidity x air pollutant interactions has been the lack of a humidification system suitable for open-top chambers or other field exposure systems. Field projects to date have concentrated on yield responses to different air pollutant concentrations, with essentially no effort being made to evaluate modifications in the exposure system appropriate for controlling humidity.

Overall, the temporal and especially geographical differences in humidity make it difficult to predict the relative effects of specific air pollutant levels in California. It is also especially difficult to interpret the applicability of air pollutant effects in California if they are based on field research from areas of the United States with higher relative humidity levels than in California.

The California Air Resources Board (CARB) currently is developing a comprehensive plan for assessing crop losses due to air pollutants throughout the State. Environmental factors such as humidity will be considered in crop loss assessments; thus, data regarding humidity effects on crops could possibly improve the accuracy of crop loss estimates.

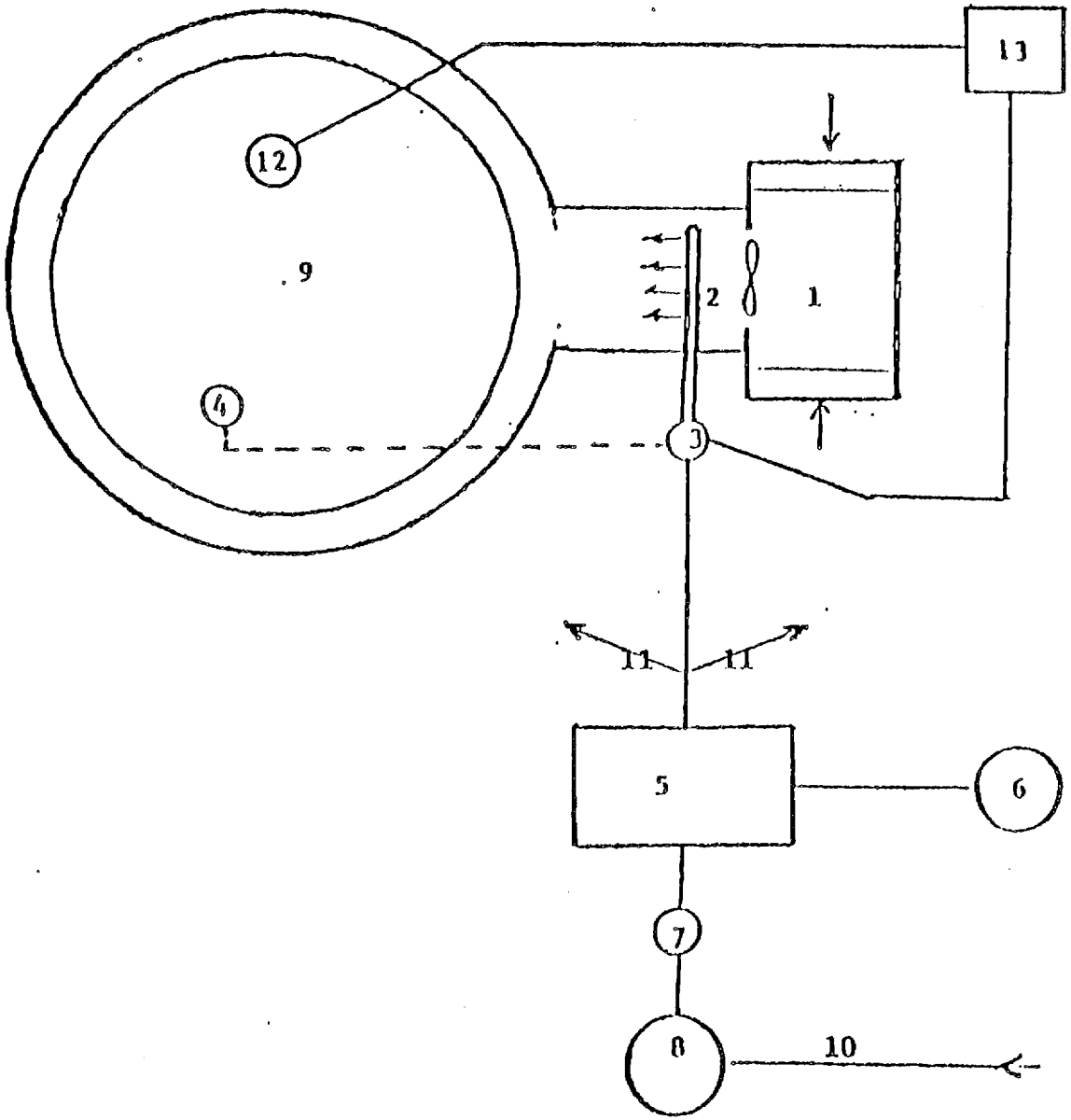
In a previous pilot project, a field humidification system was developed for use with open-top field chambers at the University of California, Riverside (22). The humidification system consisted of an extended length blower box, humidifier-humidstat system including modulating valve, steam lines, steam boiler and heated water reservoir, water softener, and propane fuel tank (Figure 1). The system was tested extensively over a wide range of relative humidities. There was little excess heating of the air and little reduction of the air pollutant level in the chamber when the steam was injected. No liquid water entered the chamber. The system was documented in terms of propane, water, and power use for humidification, and construction costs for humidification per chamber were determined.

The humidification system was controlled manually, as relative humidities in ambient air in Riverside were found to be uniform during daylight hours (varied less than 10% over the day under most conditions). Thus, the system worked well to provide a constant addition of humidification of from 20-60% above ambient with only manual controls. The boiler, propane source, water preparation, and main stream delivery system were adequate to supply six chambers.

A. Objectives

The primary objective of this study was to determine how much relative humidity levels affect the responses of plants to air pollutants in the field. This objective was investigated using the humidification system and the ARB open-top field chambers at the University of California, Riverside. Three specific studies were conducted to address this objective:

(1) A study was conducted during September through October 1986, with two levels of humidity (ambient, and plus 30-50%) and two levels of ozone (filtered vs. nonfiltered air). Tomatoes (Lycopersicon esculentum) were the test species.



1. Blowerbox with Filters
2. Steam Humidifier
3. Modulating Valve
4. Humidistat
5. Steamboiler
6. Fuel Tank
7. Boiler Feed Pump
8. Water Softener
9. "Open-top" Chamber
10. Domestic Water Supply
11. To Other Chambers
12. Dewpoint Sensor
13. Computer

Figure 1. Schematic design for steam humidifying system.

(2) A second study was conducted during November through January 1986-87, with two levels of humidity (ambient and plus 20% or more) and two levels of SO_2 (ambient, and a target of 0.10 ppm). Carrots (Daucus carota), wheat (Triticum aestivum), lettuce (Lactuca sativa), and onions (Allium cepa) were the test species.

(3) A third study was conducted during February through July 1987, with two levels of humidity (ambient, and plus 30%) and two levels of ozone (filtered vs. nonfiltered air). Ponderosa pine (Pinus ponderosa), Douglas fir (Pseudotsuga menziesii), beans (Phaseolus vulgaris), melons (Cucumis melo) and almonds (Prunus amygdalus) were the test species.

A subordinate objective was further development and testing of the field humidification system during the three studies.

II. METHODS

A. Modifications of the Humidification System

Construction of the expanded system began in mid-August and was completed by early December 1986. Construction included fabrication of four new inlet ducts; installation of humidifiers, controllers, and humidity sensors; construction of the overhead steam distribution system; installation of underground wiring for humidifiers; and installation of thermocouples and wires for each chamber. Testing of the system indicated that it worked well, but that there was a problem delivering steam to all chambers. The problem increased with time, but was found to be related to material clogging the water inlet duct from the water heater to the boiler. After this problem was solved, the system was capable of delivering enough steam to raise the humidity of six chambers, for example, from 20-60% on a 27°C day.

Figure 2 indicates the plot diagram for the study after all six humidified chambers were in operation, using the Spring 1987 study as the example.

B. Summer Humidity x Ozone Interaction Study

The original proposal called for this project to begin 7/16/86, with the Summer humidity x ambient ozone study to be conducted between 8/1/86 and 9/30/86. Three replicate chambers per treatment were proposed; however, even though the beginning date for the contract was 7/16/86, funds were not actually available until late August to purchase equipment for the extra humidification systems for this tomato study. Thus, the study was conducted with a single chamber per treatment, and the two months of study were extended into November 1986.

1. Plant Culture

The tomato cultivar 'Ace' was planted in plug trays on 7/28/86 and transplanted to 0.1 m diameter pots on 8/12/86 in a charcoal filtered greenhouse. On 8/29/86 the seedlings were transplanted into paper pulp pots. There were 60 larger (0.3 m diameter x 0.4 m high) pots intended to carry the plants to full harvest, and 40 smaller (0.2 m diameter x 0.2 m high) pots for an earlier harvest. The seedlings were ~0.1 m high at

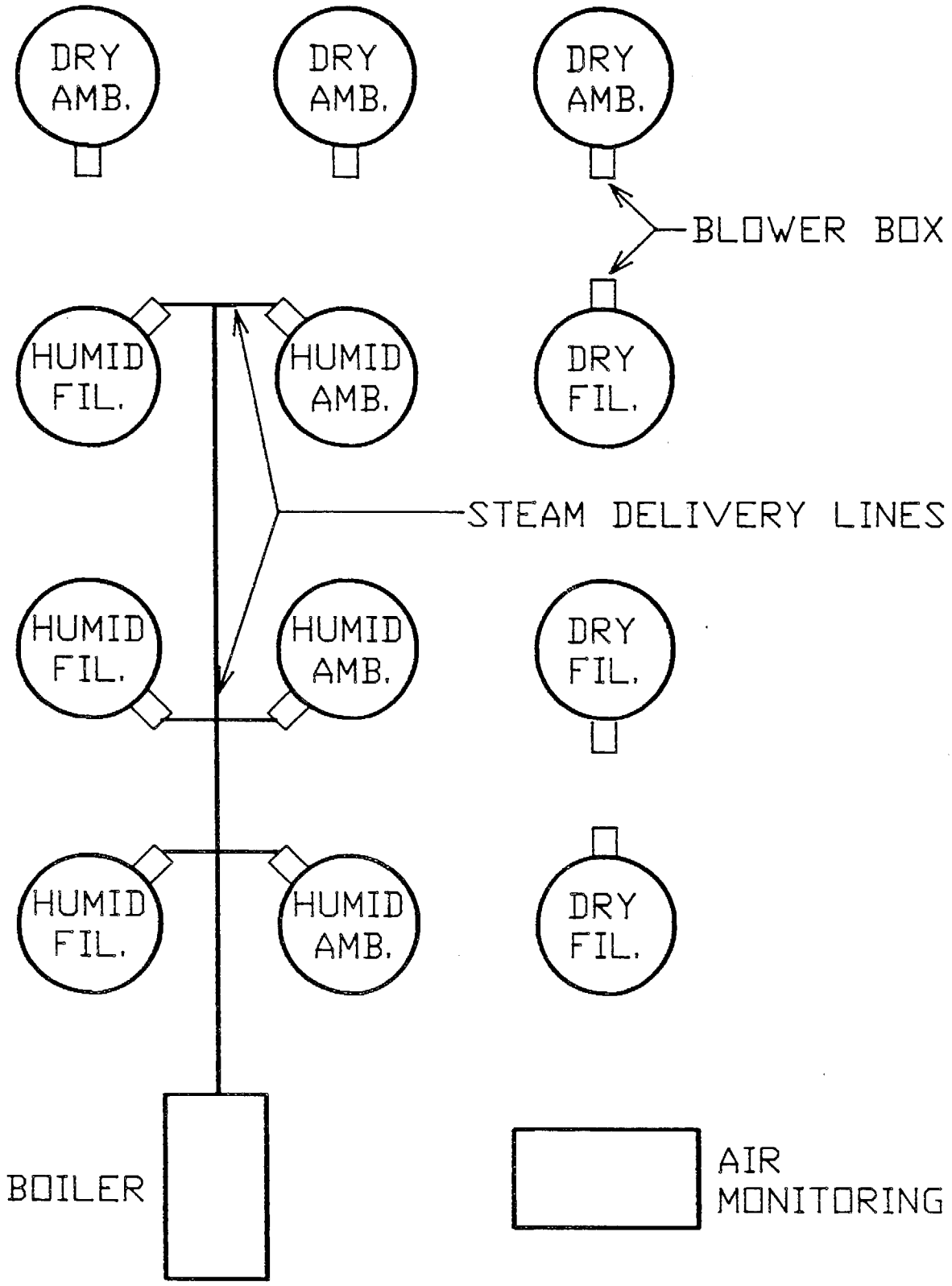


Figure 2. Diagram of experimental plan for humidity studies.

this time. The potting mix was UC Mix II containing all macro- and micronutrients.

The tomato plants were transferred to the open-top chambers and the outside plot in September, 48 days after seeding. There were initially 10 larger and eight smaller pots for each of the five plots. The plants remained in the chambers until the final harvest on 11/12/86. The plants received routine watering, fertilization, and pest control as required.

2. Humidity and Air Pollution Exposures

Four open-top field chambers were used for this study. Two were equipped with dry steam to raise humidity, using the system described in a previous final report (22). Figure 1 indicates the basic humidification system used for this study, including propane storage tank, propane boiler, steam delivery system, humidifiers, long mixing ducts, and humidistats for manual control. Humidity was measured in each chamber and at the outside plot using a signal fed to a strip chart recorder.

One each of the dry steam (humid) and no steam (dry) chambers was equipped with a charcoal filter to remove ambient oxidants, primarily ozone. Ozone was monitored continuously with a Dasibi® ultraviolet absorption ozone analyzer (Model 1003 AH) calibrated with a Dasibi® transfer standard maintained by the CARB office in El Monte, CA. The ozone data were recorded on a strip chart recorder and with an Apple® IIe computer system connected to a Cyborg ISAAC® analog/digital interface unit.

Before the experiment began, flow measurements were made to determine differences in air transport between the four chambers. The carbon monoxide dilution system described by Olszyk et al. (14) was used. Since the presence of charcoal filters caused a reduction in flow rate of ~15%, fiberglass restrictors were installed in the nonfiltered (ambient) chamber ducts to equalize flows. The final flow rate was established at 57.36 m^3 min^{-1} for an air exchange rate of ~3.3 times per minute.

The following treatments were applied: dry steam added to ambient air (humid, ambient), dry steam added to charcoal filtered air (humid, filtered), no steam added to ambient air (dry, ambient), and no steam added to filtered air (dry, filtered). There was also an outside plot with no steam and ambient air to serve as a check of chamber effects on plant growth (dry, outside). The dry steam was added at a rate sufficient

to increase the relative humidity by ~30% between 1000 and 1600 on 37 days when the ambient humidity was below about 30%. If the day was overcast and relative humidity did not decrease rapidly in the early morning, then no steam was added. The humidity addition system was under manual control.

The "ambient" ozone concentration was actually increased slightly with the addition of 0.05 ppm ozone while the humidification system was in operation between approximately 1100 and 1600. This was necessary as the ambient ozone concentrations were low due to the overcast and cool weather which does not cause the buildup of photochemical oxidants. Ozone was added at the same concentration to both the humid and dry "ambient" chambers.

Data from the humidity and ozone measurements are shown in Table 1. The ozone concentration during the study was approximately the same in the humid and dry ambient chambers, indicating the lack of significant line loss. The ozone concentration in the filtered chambers was only about 9% of that in outside air, indicating the efficiency of the chambers in removing ambient ozone. The ozone concentration was about 20% higher in the "ambient" chambers than in outside air due to the added 0.05 ppm ozone for five to six hours per day for half the experiment.

The humidity level was 35% higher in the humidified vs. dry chambers during half the experimental days when humidity was added (Table 1). The humidity level in humidified chambers was ~15% higher than in dry chambers on a whole experiment basis. The humidity data were only for the period of 1300-1400 to correspond to the 1300 data available through the crop loss assessment project. However, the 1300 data also indicate the average humidity to which the plants were exposed at midday when ozone concentrations are increasing and plant sensitivity to pollutants is normally at a peak.

3. Environmental Measurement

Important environmental conditions were measured routinely near the chamber at the citrus site in order to provide a basis for humidity and ozone effects in light of ambient weather conditions. Air temperature was measured with iron-constantan thermocouples, light intensity with a LI-COR® LI-190SB quantum sensor, and relative humidity using data from a General Eastern chilled mirror dewpoint sensor in conjunction with the air temperature measurements.

Table 1. Average Pollutant Concentrations and Humidity Levels for Humidity x Air Pollution Studies

Study	Target Humidity	Target Pollutant	Humidity[a] (%)	Pollutant[b] (ppm)
		O_3		
Summer	Humid	Ambient	63 ± 8[c]	0.054 ± 0.017
9/12/86-	Humid	Filtered	-	0.008 ± 0.005
11/6/86	Dry	Ambient	28 ± 8	0.055 ± 0.018
	Dry	Filtered	-	0.004 ± 0.004
	Dry	Outside	-	0.046 ± 0.015
		SO_2		
Winter	Humid	0.10 ppm	62 ± 5[d]	0.101 ± 0.004
12/9/86-	Humid	Zero	-	0.001 ± 0
2/8/87	Dry	0.10 ppm	22 ± 7	0.121 ± 0.008
	Dry	Zero	-	0.001 ± 0
		O_3		
Spring	Humid	Ambient	52 ± 14[e]	0.062 ± 0.001
4/1/87-	Humid	Filtered	-	0.016 ± 0.004
7/31/87	Dry	Ambient	27 ± 10	0.065 ± 0.001
	Dry	Filtered	-	0.015 ± 0.001
	Dry	Outside	-	0.075 ± 0.0003

[a]Humidity is average ± SD at 1300-1400 for days when humidity was added. The humidity level in the humid/filtered treatment was assumed to be the same as humid/ambient, and dry/filtered the same as dry/ambient.

[b]Values in summer are ± SD for one chamber over 40 days or one outside plot over 36 days. Values in winter and spring are ± SD for three chambers or outside plots. Ozone data are for 0800-2000 over the entire exposure period. Sulfur dioxide data are for the 160.5 hours on the 24 days when the pollutant was added to the chambers.

[c]Humidity is average ± SD for 28 days. Humidity was added for 150 hours on 28 days.

[d]Humidity is average ± SD for 13 days when measured. Humidity was added for 160.5 hours on 20 days.

[e]Humidity is average ± SD for 55 days when measured. Humidity was added for 276.5 hours on 56 days.

The environmental data were processed and stored with the same computer-interface system used for the ozone data. These data are available for analysis if necessary.

4. Plant Response Measurement

Plant responses were evaluated in terms of leaf injury, growth, biomass production, fruit yield, and physiological response parameters. Leaf injury was quantified by examining leaves and giving them a numerical rating as to percentage of leaf area injured. Leaf injury also was evaluated by determining if leaves were chlorotic and then counting the number of senescent (chlorotic) and normal green leaves per plant. The percentage of chlorotic leaves was then determined.

Plant growth was determined as leaf area, stem length, internode length, and leaf numbers. Biomass was determined as fresh and dry weights for leaves and stems separately, and as a total, per plant. Yield was determined as numbers and weight of flowers or green fruit. The flowers and fruit were divided into different size classes on different dates. Only green fruits were present at the time of harvest due to the late start of the study and cool temperatures in September and October, which inhibited fruit ripening. Preliminary measurements were made for plant growth on three dates between 9/30/86 and 10/17/86. The plants in smaller pots were harvested and measured on 10/21/86, and the plants in the larger pots (main harvest) were measured on 11/12/86. Only the harvest data for the larger plants are reported here.

Physiological parameters included photosynthesis, transpiration, and stomatal conductance as measured with a LI-COR® LI-6000 portable photosynthesis system. Measurements were made on six dates between 9/11/86 and 10/28/86 on fully expanded leaves with minimal injury. Leaf water potential was measured with a pressure bomb (Scholander et al. 1965) on 9/30/86 and 10/16/86. Chlorophyll fluorescence was measured once on 10/29/86 (on a pilot basis) using a new device on loan from Native Plants Incorporated of Salt Lake City, UT.

C. Winter Humidity x Sulfur Dioxide Interaction Study

1. Plant Culture

Four species were used for this study: wheat (Triticum aestivum cv. 'Yecora roja'), carrots (Daucus carota cv. 'Imperator'), lettuce

(Lactuca sativa cv. 'Empire'), and onions (Allium cepa cv. 'White Globe'). All species were started from seed in a charcoal filtered greenhouse between 10/14/86 and 10/21/86, with multiple seeds per eight-liter pulp pot. The pots were thinned and transferred outside on 11/21/86. Initially, they were transferred to four ambient open-top chambers and randomly redistributed to all three chambers and outside plots, for each of the four treatments, on 12/4/86 when the exposures began. After redistribution there were five pots per chamber or outside plot, with multiple plants per pot. All plants were irrigated, fertilized, and treated for pests as necessary during the course of the study.

Plants of alfalfa (Medicago sativa cvs. 'Moapa' and 'Mesa Sirsa') and potato (Solanum tuberosum cv. 'White Rose') were started from crowns and tuber pieces, respectively, also in mid-October 1986. Initially, there were five pots per cultivar placed in the chambers at the same time as the other four species. However, many of the potato plants were damaged because of low temperature and, thus, all plants were discarded during the course of the winter study. The alfalfa plants were maintained during the entire winter study. However, they grew slowly and were not ready for harvest until one month after the end of the exposures, i.e., mid-February. Thus, the data were not used for this study because the plants had an extra one-month of ambient air exposure which was thought to overshadow any humidity or sulfur dioxide effects.

2. Humidity and Air Pollutant Exposures

There were four chamber treatments: added humidity and ambient (essentially zero) sulfur dioxide, ambient (dry) humidity and zero sulfur dioxide, added humidity and added target of 0.10 ppm sulfur dioxide, and dry humidity and added target of 0.10 ppm sulfur dioxide. There were also outside control plots. Each treatment was replicated in three chambers or outside plots.

Sulfur dioxide was generated from a tank of liquid sulfur dioxide heated and thermostatically controlled to a constant temperature. The sulfur dioxide concentration was regulated by flow meters for each chamber and delivered to the chambers in dry air supplied by a heatless air dryer. Sulfur dioxide was monitored with a Meloy flame photometric analyzer with data recorded via the interface/computer system. Sulfur dioxide was delivered to the chambers only when extra humidity was

added. The concentration was ~0.10 ppm sulfur dioxide between approximately 1000 and 1500. Other pollutants in the ambient air also were measured and data stored by the interface/computer system. The pollutants and ozone were measured by a Dasibi® ultraviolet analyzer, nitric oxide and nitrogen dioxide by a Monitor Labs fluorescent analyzer, and peroxyacetyl nitrate (PAN) by a gas chromatograph. The PAN data were recorded by a strip chart recorder.

The sulfur dioxide concentration in the dry/polluted chambers averaged 0.12 ppm on the days of exposure, 20% higher than the target concentration (Table 1). The sulfur dioxide concentration in the humid/polluted chambers averaged 0.10 ppm, 16% lower than in the dry chambers. This difference was not due to differences in pollutant concentrations entering the different chambers, as all flows were similar and adjusted for chamber air flow. Instead, the reduction probably was due to loss of sulfur dioxide to sampling lines leading from the humid chambers to the analyzers. This loss would be greater than any loss of ozone, as sulfur dioxide is much more soluble in water than ozone. Furthermore, the sulfur dioxide line loss occurred in winter when cooler ambient temperatures encourage condensation of water vapor in lines between the chambers and instrument building. In contrast, the ozone exposures were in warmer spring, summer, and fall months when less condensation of water vapor would be expected to occur within sampling lines.

Humidity was delivered from the modified dry steam delivery system to six humidified chambers (Figure 2). Approximately 40% extra humidity was added to the humidified chambers whenever the ambient humidity went below 30%, thus attaining levels of 55-60% between the hours of 1100 and 1600. The humidity level in humidified chambers was 15% higher than in dry chambers on a whole experiment basis, similar to the increase found in the Fall ozone study.

3. Environmental Measurements

Environmental measurements were as described for the summer humidity x ozone study.

4. Plant Response Measurement

Each species was harvested on a different date based on the time for full development of plants. The response measurements were selected to indicate yield of marketable part of plant and plant growth and

biomass accumulation. Lettuce was harvested on 2/6/87, with the following response parameters: plant diameter, total plant fresh weight, head fresh weight, and total plant dry weight.

Carrots were harvested on 2/13/87, with the following response parameters: total root fresh weight per pot (three to six plants), total top fresh weight per pot, and total top dry weight per pot. Total fresh weight per pot, average root fresh weight per plant, average top fresh weight, average top dry weight, and average plant total fresh weight were calculated from the basic parameters.

Onions were harvested on 2/18/87 with the following response parameters: total fresh weight per pot (four to five plants). Average fresh weight per plant was calculated from this parameter.

Wheat was harvested on 2/20/87, with the following response parameters: number of tillers per pot (approximately three plants), number of heads per pot, average maximum height of plants per pot, total vegetative fresh weight per pot, total vegetative dry weight per pot, and weight per ear. Total dry vegetative weight/total fresh vegetative weight was calculated from the basic parameters.

Physiological response measurements were made for stomatal conductance and transpiration on wheat, lettuce, and onions. The LI-COR® 1600 porometer was used for these measurements; data were taken on fully expanded leaves with little or no visible injury.

D. Spring Humidity x Ozone Interaction Study

1. Plant Culture

Five species were used for this study: almonds (Prunus dulcis cv. 'Nonpareil'), ponderosa pine (Pinus ponderosa), Douglas fir (Pseudotsuga menziesii), beans (Phaseolus vulgaris cvs. 'Great Northern' and 'Pinto'), and cantaloup melons (Cucumis melo). The almonds were obtained as one-year-old bare root seedlings from a commercial nursery on 2/10/87 and planted on 2/11/87 and 2/12/87 in large (0.30 m diameter x 0.40 m high) pulp pots. The ponderosa pine and Douglas fir were obtained as one-year-old bare root seedlings from the California Department of Forestry in January 1987, and potted in 0.15 x 0.23 m pulp pots. For the first group of beans, there were two strains of 'Great Northern', one believed to be ozone susceptible (S), and one ozone tolerant (T). For the

second group of beans, the same ozone susceptible and resistant strains of 'Great Northern' as well as 'Pinto' beans were grown. The beans were seeded on 3/31/87, using similar pots. The melons were seeded on 6/8/87, using the same pulp pots. The almonds, ponderosa pine, and Douglas fir were kept outside in ambient air until moved into the open-top chambers on 4/1/87. The beans were kept in a greenhouse with charcoal filtered air until moved to the chambers on 4/1/87, with seedlings beginning to emerge from the soil on 4/7/87. The melons were seeded on 6/8/87 and moved from the charcoal filtered greenhouse to the chambers on 6/29/87.

All plants received irrigation, fertilization, and pest control as required. The almond pots were set on the soil surface; for all other species, the pots were set into plastic liners sunk into the soil. There were five pots per species per chamber or outside plot.

2. Humidity and Air Pollution Exposures

There were four chamber treatments: added humidity and ambient ozone, ambient (dry) humidity and filtered air (low ozone), added humidity and filtered air, and dry humidity and ambient ozone. There also were outside control plots. Each treatment was replicated in three chambers or outside plots.

Ozone was monitored for all chambers and outside plots as described for the Fall humidity x ozone study in Section II.B. Sulfur dioxide, nitric oxide, nitrogen dioxide, and PAN were monitored in the ambient air as described in Section II.C and are available if needed. All pollutant data were stored by the interface/computer system, except for the PAN data which were recorded by a strip chart recorder. The ozone concentration during the Spring study was approximately the same in the humid and dry ambient chambers, again indicating the lack of significant line loss (Table 1). The ozone concentration in the filtered chambers was about 24% of that in outside air.

Relative humidity (~30%) was added to the chambers between 1100 and 1600 on days when the humidity rapidly decreased to below 30% as described in Section II.B. This maintained humidity levels of 50-60% in the chambers (Table 1). Humidity was added to the chambers on 276.5 hours over 56 of the 122 days of the study.

3. Environmental Measurements

Environmental measurements were as described for the Summer humidity x ozone study.

4. Plant Response Measurement

Almonds were harvested between July 24 and 31, 1987. Leaf injury was measured as percent healthy leaves, with data taken from three branches per tree. The number of healthy leaves and total leaves (measured as number of nodes) on the three branches were counted and percent healthy leaves determined as healthy/total leaves. Leaf injury was determined as a chlorotic mottling. Fresh weights were determined at harvest for all leaves, all branches, and trunk above the graft. Height of tree above the graft and trunk diameter also were measured. Dry weights were determined for leaves, branches, and trunk after drying for ~12 days. Total tree fresh weight and percent fresh/dry biomass were calculated from the individual tree organ weights.

Ponderosa pine and Douglas fir were harvested on 7/17/87 and 7/21/87, respectively. Needle injury symptoms were noted at the time of harvest. For each species, new and old growth (needles and branches) were harvested separately and fresh weights taken immediately. Dry weights were measured after drying for 18 and 15 days, respectively, for the pine and Douglas fir. Total growth weights and percent new growth weight (new/old) were calculated from the individual growth data.

Melons were harvested on 7/31/87 from the humid chambers, and nondestructive data were taken from the dry chambers on 8/7/87. The melons in the dry chambers were not harvested as their exposures continued until the end of August to obtain data for the ARB Crop Loss Project. All vines per plant were laid out on the ground and total vine length per plant was measured. The number of flowers and fruit per plant also were measured. The fruits were still very small at this stage of development and were not weighed.

Two groups of beans were grown. For the first group, a first pick of beans from both cultivars was made on 6/15/87 and 6/16/87. The number of beans and total bean fresh weight per plant were measured immediately, and dry weight measured after several weeks of drying. The percentage dry/fresh weight was calculated from the individual weight data. A second pick of beans was made for group one on 6/28/87, but weights were not taken.

Plants from all three cultivars of the second group of beans were harvested on 7/23/87. The number and fresh weight of beans and the fresh weight of vegetative biomass were measured immediately. The dry weights of beans and vegetative biomass were measured after several weeks of drying. The dry and fresh weights per bean and percentage of dry/fresh biomass (beans plus vegetative plant) were calculated from the individual bean and biomass data. The bean plants were rated for visible ozone injury symptoms (chlorosis and necrosis) on 7/22/87. Whole plants were rated on a 0-100% leaf area injured basis in increments of 5%. Physiological response measurements were made for green, mature leaves of almonds and beans. The LI-COR® 1600 steady state porometer was used with stomatal conductance and transpiration as the response parameters. Measurements were made on six days for almonds and seven days for beans, using fully expanded leaves with as little visible injury as possible.

E. Statistical Analysis

The basic experimental design for all three studies was a completely randomized design with five treatments: no air pollutant and ambient (no added) humidity, no air pollutant and added humidity, air pollutant added and ambient humidity, air pollutant and added humidity, and outside check plots with ambient pollutants and ambient humidity. General statistical analysis procedures were as described by Steel and Torrie (19). Even though the treatments were assumed to be randomized among chambers and outside plots for the analysis, the actual locations of the different treatment chambers and outside plots were fixed in space for all studies. This was due to physical limitations of the delivery system to add humidity to chambers and the permanent nature of the chambers (Figure 2).

Each air pollutant x humidity treatment was replicated in three chambers, and the outside treatment was replicated in three plots for the Winter and Spring studies. There was no replication for the Fall 1986 study, as it had to get underway while added chamber humidification parts were still being obtained. There were 10 pots per chamber and outside plot for the Fall study, and approximately five pots per species per chamber and outside plot for the Winter and Spring studies. For some species in the Winter study, there were multiple plants (three to five per

pot). Parameters expressed on a per plant basis were calculated as total response per pot. The chamber was the experimental unit for detecting treatment differences in the analysis of variance for most of the Winter and Spring data. The individual plant (pot) was the experimental unit for the Fall tomato data and for some species in the Winter and Spring studies where there was highly unbalanced replication between chambers. For those species, there were dead plants, lost data, or unequal numbers of observations due to lack of time to make all measurements in all chambers. This resulted in less than three chambers, or fifteen total plants measured for some treatments and/or responses.

Data from plants growing near the edges of the chambers were not eliminated from this study, as the plants were grown in pots as described earlier. This allowed for random distribution of plants within the chamber, and lack of soil effects on plants growing near the chamber wall where moisture tended to collect. In previous studies where plants were grown in the ground in the same location in each chamber, plants near the edges of the chambers were not used in the analysis because their growth and development were different from that of plants in the center of the chamber.

The analysis of variance for tomatoes included the following treatments: dry ambient, dry filtered, humid ambient, humid filtered, and outside. The air, humidity, and air x humidity contrasts were a form of two-way analysis of variance within the larger analysis. The dry ambient vs. outside contrast was intended to detect chamber effects on plant response. The error term was based solely on sampling error, as there was only one chamber per treatment. There usually were 10 plants per treatment; however, the same design could still be used with variable plants per treatment. The partitioning of the degrees of freedom for the tomato study are shown at the top of the next page.

The same analysis of variance was used for tomato physiological measurements; however, there were four to five plants measured per treatment with subsequent reduction in sampling error and total degrees of freedom. The tomato physiological data also were analyzed across six measurement days. In this case, the day effect was simply ignored as there were differing numbers of measurements per day. Instead, the sampling error and total df were simply increased to represent the larger number of observations.

Source of Variation	df
Treatment	
Air (filtered vs. ambient)	4
Humidity (dry vs. humid)	(1)
Air x Humidity	(1)
Dry Ambient vs. Outside	(1)
Sampling Error	45
TOTAL	49

The complete analysis of variance for the winter and spring studies included the same treatments and contrasts as the Fall tomato study. The partitioning of degrees of freedom for the complete analysis of variance when all data were present is shown below:

Source of Variation	df
Treatment	4
Air (filtered vs. ambient)	(1)
Humidity (dry vs. humid)	(1)
Air x Humidity	(1)
Dry Ambient vs. Outside	(1)
Chamber Error	10
Sampling Error	60
TOTAL	74

This analysis assumed that data were present for all five plants in each of three replicate chambers or outside plots for all five treatments. The chamber error was used to determine the significance of the treatment effects; the sampling error was based on the subsamples within each chamber or outside plot.

Occasionally, missing plants necessitated changes in this basic design. For example, for some winter porometer data, there were sometimes two chamber replicates. There were also highly variable numbers of measurements for other winter and spring porometer measurements. This resulted in omission of the chamber error altogther and the use of the basic tomato statistical analysis design. The Spring Douglas fir growth and yield data had many missing data points due to dead plants which resulted in elimination of the chamber error term.

The Spring study included several cultivars of beans in order to determine the influence of plant genotype on the humidity and air effects. The first group of beans had two cultivars (ozone susceptible and tolerant), whereas the second group had three cultivars (ozone susceptible, ozone tolerant, and pinto). Both groups had three plants of each cultivar in each of three replicate chambers or outside plots. There were also two df for the factor corresponding to the three replicates each of the chambers and outside plots. The bean analysis of variance included cultivar and cultivar x treatment interaction terms as shown on the next page for the second group of plants. The ANOVA for the first group of plants was similar, except that the terms involving cultivar, the sampling error, and total df were lower because only two cultivars were present.

Source of Variation	df
Treatment	4
Air (filtered vs. ambient)	(1)
Humidity (dry vs. humid)	(1)
Air x Humidity	(1)
Dry Ambient vs. Outside	(1)
Replicate	2
Chamber Error	8
Cultivar	2
Cultivar x Treatment	8
Cultivar x Air	(1)
Cultivar x Humidity	(1)
Cultivar x Air x Humidity	(1)
Cultivar x Dry Ambient x Outside	(1)
Error Cultivar x Treatment	20
Sampling Error	90
TOTAL	134

III. RESULTS AND DISCUSSION

A. Summer Humidity x Ozone Interaction Study

1. Injury, Growth, and Yield Effects

a. Ozone Effects

Ozone produced visible leaf injury on tomatoes during the entire study, with symptoms consisting generally of a chlorotic mottle of lower leaves. This injury was quantified on 10/21/86 and at the final harvest. At the preliminary harvests, ozone produced a decrease in leaf length on both 9/23/86 and 9/30/86, as well as a decreased number of fruit on 10/10/86 (Tables 2 and 3). Ozone also decreased the leaf total dry weight, average dry weight, and average fresh weight; and increased stem length and leaf injury.

At the final harvest, the primary ambient ozone effect on tomatoes was a generalized leaf chlorosis followed by premature leaf senescence. As shown in Table 4, ozone had a highly significant effect on leaf injury, with a high injury rating for ambient air plants and no injury for filtered air plants (Table 5). Ozone also affected plant vegetative biomass production, with a statistically significant effect on six of the nine leaf and stem weight parameters; leaves were primarily affected (Table 4). In general, the weights were lower for ambient ozone plants compared to filtered air plants (Table 5).

b. Humidity Effects

Humidity in general increased vegetative plant growth and biomass as indicated by data from both the preliminary and final harvests (Tables 2 and 4, respectively). For the preliminary harvests with increased humidity, there was a significant increase in height on 9/23/86 and 10/10/86 (Table 3). However, humidity resulted in decreased fruit set on 10/21/86, as shown by the lower number of fruit in humid chambers vs. dry chambers.

At the final harvest, there were statistically significant effects on leaves, stems, and flowers (Tables 4). Increased humidity generally resulted in increased growth and biomass, except for a decreased leaf area compared to dry air (Table 5). There was an apparent statistically significant increase in leaf injury solely due to humidity on both 10/21/86 and the final harvest. However, this effect was a byproduct of the very large humidity x ozone interaction on injury, as there was no injury

Table 2. Analysis of Variance Results for Tomatoes Exposed to Humidity and Ambient Ozone - Preliminary Harvests[a]

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamber Effect
			9/23/86		
1	Height	**	NS	**[b]	**
2	Leaf Length	NS	***	NS	*
3	# Flowers (>3 mm)	NS	NS	NS	NS
			9/30/86		
1	Height	NS	NS	NS	***
2	Leaf Length	NS	**	NS	NS
3	Lateral Length	NS	NS	NS	**
4	# Flowers (>3 mm)	NS	NS	NS	***
			10/10/86		
1	Height	NS	NS	NS	*
2	# Fruits	NS	*	*[b]	NS
3	# Flowers (>3 mm)	NS	NS	NS	NS
4	Lateral Length	NS	NS	NS	NS
			10/21/86		
1	# Leaves	NS	NS	NS	NS
2	Fresh Wt Leaves	NS	NS	NS	NS
3	Dry Wt Leaves	NS	**	NS	NS
4	Leaf Area	NS	NS	NS	NS
5	Av % Leaf Injury	***	***	***[b]	***
6	Fresh Wt Stems	NS	NS	*[b]	NS
7	Dry Wt Stems	NS	NS	NS	NS
8	Stem Length	**	*	*[b]	NS
9	# Flowers	NS	NS	NS	NS
10	# Fruit	*	NS	NS	*
11	Av Fresh Wt Leaves	NS	**	NS	NS
12	Av Dry Wt Leaves	NS	**	NS	NS

(continued)

Table 2 (concluded) - 2

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamber Effect
13	Av Leaf Area	NS	NS	NS	NS
14	Total Fresh Wt Plant	NS	NS	NS	NS
15	Total Dry Wt Plant	NS	NS	NS	NS
		Summary			
8	Biomass (# sig)	0	3	1	0
11	Growth (# sig)	2	3	2	5
6	Fruit (# sig)	1	1	1	2
1	Injury (# sig)	1	1	1	1

[a]Based on analysis of variance with one chamber per treatment and five plants per chamber. Parameter followed by *, **, and *** is statistically significant at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]Greater ozone effect in humidified chamber.

Table 3. Effects of Humidity and Ambient Ozone on Tomatoes - Preliminary Harvests Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
			9/23/86			
1	Height (m)	0.38 ± 0.03	0.36 ± 0.03	0.33 ± 0.03	0.36 ± 0.02	0.29 ± 0.03
2	Lf Leng (m)	0.38 ± 0.40	0.40 ± 0.02	0.37 ± 0.03	0.40 ± 0.02	0.34 ± 0.02
3	Flowers (#)	8 ± 2	8 ± 2	7 ± 1	8 ± 2	6 ± 2
			9/30/86			
1	Height (m)	0.48 ± 0.03	0.49 ± 0.02	0.46 ± 0.05	0.47 ± 0.04	0.37 ± 0.03
2	Lf Leng (m)	0.39 ± 0.02	0.42 ± 0.03	0.40 ± 0.02	0.42 ± 0.03	0.39 ± 0.02
3	Flowers (#)	12 ± 3	10 ± 2	12 ± 2	11 ± 1	7 ± 2
4	Lf Leng (m)	0.18 ± 0.05	0.18 ± 0.04	0.17 ± 0.05	0.17 ± 0.05	0.11 ± 0.03
			10/10/86			
1	Height (m)	0.59 ± 0.10	0.63 ± 0.13	0.60 ± 0.02	0.60 ± 0.02	0.51 ± 0.04
2	Fruit (#)	2 ± 1	4 ± 2	2 ± 0	2 ± 2	1 ± 1
3	Flowers (#)	22 ± 4	19 ± 4	16 ± 3	18 ± 2	17 ± 6
4	Lf Leng (m)	2.09 ± 0.29	2.27 ± 0.31	2.27 ± 0.34	2.05 ± 0.23	1.86 ± 0.22

Table 3 (concluded)

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
			10/21/86			
1	Leaves (#)	60 ± 6	50 ± 8	51 ± 7	53 ± 3	46 ± 6
2	Lf FW (g)	306 ± 25	312 ± 30	285 ± 22	314 ± 10	265 ± 30
3	Lf DW (g)	34 ± 4	38 ± 2	34 ± 3	38 ± 1	31 ± 3
4	Lf Area (m^2)	0.51 ± 0.04	0.52 ± 0.06	0.47 ± 0.07	0.51 ± 0.03	0.41 ± 0.08
5	Av Injury (%)	10.1 ± 4.8	0	1.3 ± 0.7	0	0.1 ± 0.3
6	Stem FW (g)	223 ± 17	194 ± 12	182 ± 18	200 ± 31	186 ± 21
7	Stem DW (g)	21.5 ± 1.5	19.4 ± 3.8	19.0 ± 2.8	20.1 ± 2.9	18.3 ± 1.1
8	Stem Leng (m)	348 ± 12	257 ± 21	251 ± 24	247 ± 10	298 ± 87
9	Flower (#)	33 ± 5	28 ± 7	30 ± 6	26 ± 11	23 ± 4
10	Fruit (#)	5 ± 1	8 ± 3	9 ± 3	10 ± 2	5 ± 2
11	Lf Av FW (g)	5.16 ± 0.63	6.30 ± 0.84	5.62 ± 0.53	6.07 ± 0.42	5.75 ± 0.32
12	Lf Av DW (g)	0.57 ± 0.10	0.77 ± 0.14	0.67 ± 0.07	0.73 ± 0.07	0.68 ± 0.07
13	Lf Av Area (cm^2)	85 ± 10	104 ± 11	92 ± 14	99 ± 6	89 ± 11
14	Total FW (g)	529 ± 40	506 ± 27	467 ± 38	513 ± 38	451 ± 48
15	Total DW (g)	55.1 ± 5.0	57.2 ± 5.1	53.0 ± 5.4	57.9 ± 3.6	49.3 ± 2.7

[a]Mean ± SD of five plants, all in one chamber per treatment.

Table 4. Analysis of Variance Results for Tomatoes Exposed to Humidity and Ambient Ozone - Final Harvest[a]

Parameter #	Parameter Name	Effect: Humidity	Air	Air x Humidity	Chamber
		Growth Parameters			
1	Leaf area, total	NS	**	NS	*
2	Leaf area, av	***	***	NS	*
3	Leaves, total #	***	NS	NS	NS
4	Stem length	**	NS	NS	NS
		Injury Parameters			
5	Leaves, normal #	***	*	NS	NS
6	Leaves, senescent #	NS	NS	**[b]	NS
7	Leaves, chg % inj.	***	***	***[b]	**
8	Leaf injury, av	***	***	***[b]	***
		Biomass Parameters			
9	Leaf wt, fresh	NS	**	NS	NS
10	Leaf wt, dry	NS	***	NS	NS
11	Lea wt, fr avg	**	***	NS	NS
12	Stem wt, fresh	*	NS	NS	NS
13	Stem wt, dry	NS	NS	NS	NS
14	L + S wt, fresh	NS	**	NS	NS
15	L + S wt, dry	NS	*	NS	NS
16	L + S wt, dry/fr	*	NS	NS	NS
17	Total Plant Wt, fr	NS	**	NS	***
		Fruit Parameters			
18	Flower #	*	NS	NS	***
19	Fruit < 1.0 cm #	*	NS	NS	**
20	Fruit > 1.0 cm #	NS	NS	NS	***
21	Fruit wt	NS	*	NS	***

(continued)

Table 4 (concluded) - 2

Parameter #	Parameter Name	Effect: Humidity	Air	Air x Humidity	Chamber
		Summary			
9	Biomass (# sig)	3	6	0	1
4	Growth (# sig)	3	2	0	2
4	Fruit (# sig)	2	1	0	4
4	Injury (# sig)	3	3	3	2

[a]Based on analysis of variance with one chamber per treatment and 10 plants per chamber. Parameters followed bt *, **, and *** are statistically significant at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]Greater ozone effect in humidified chamber.

Table 5. Effects of Humidity and Ambient Ozone on Tomatoes - Final Harvest Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
1	Lf area (m^2)	11.1 ± 1.6	13.6 ± 2.4	11.4 ± 2.3	12.6 ± 2.0	9.4 ± 1.5
2	Lf area av (m^2)	1.25 ± 0.13	1.62 ± 0.28	1.58 ± 0.14	1.80 ± 0.21	1.40 ± 0.17
3	Leaves (#)	90 ± 18	84 ± 9	72 ± 10	71 ± 12	68 ± 8
4	Stem length (m)	6.8 ± 1.9	6.4 ± 0.9	5.4 ± 1.2	5.3 ± 1.2	5.4 ± 0.6
5	Leaves, normal (#)	81 ± 15	80 ± 10	68 ± 10	66 ± 11	62 ± 9
6	Leaves, senes (#)	9 ± 4	4 ± 3	4 ± 2	5 ± 3	5 ± 2
7	Leaves chg % inj	2870 ± 681	0	591 ± 243	0	104 ± 60
8	Leaf injury (%)	36 ± 7	0	9 ± 4	0	2 ± 1
9	Leaf FW (g)	794 ± 106	925 ± 131	775 ± 136	858 ± 114	691 ± 102
10	Leaf DW (g)	87 ± 12	109 ± 18	87 ± 13	96 ± 14	84 ± 11
11	Leaf av FW (g)	9.0 ± 1.0	11.1 ± 1.7	10.8 ± 0.7	12.3 ± 1.5	10.3 ± 1.3
12	Stem FW (g)	666 ± 162	647 ± 61	590 ± 98	556 ± 87	540 ± 43
13	Stem DW (g)	79 ± 15	89 ± 16	79 ± 17	75 ± 15	68 ± 5
14	Leaf + Stem FW (g)	1460 ± 257	1573 ± 155	1364 ± 220	1414 ± 194	1230 ± 140
15	Leaf + Stem DW (g)	166 ± 25	198 ± 27	166 ± 29	171 ± 27	151 ± 12
16	Leaf + Stem D/F	0.11 ± 0.01	0.13 ± 0.02	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01
18	Plant wt (g)	2568 ± 336	2871 ± 348	2561 ± 303	2830 ± 359	1875 ± 215
18	Flowers (#)	91 ± 26	91 ± 11	80 ± 18	72 ± 17	118 ± 102
19	Fruit <1 cm (#)	7 ± 3	10 ± 6	5 ± 2	6 ± 3	10 ± 4
20	Fruit >1 cm (#)	22 ± 4	24 ± 2	25 ± 4	25 ± 4	17 ± 4
21	Total FW (g)	1108 ± 104	1283 ± 298	1228 ± 270	1418 ± 261	644 ± 166

[a]Mean ± SD for 10 plants, all in one chamber per treatment.

specifically due to humidity as evident by comparing the humid filtered and dry filtered treatments (Table 5).

c. Humidity x Ozone Interactions

There were a few significant interactions at the preliminary harvests (Table 2). Generally, the highest growth was in the humid ambient chamber and the lowest in the dry ambient chamber (number of flowers on 10/10/86, fresh weight of stems, and stem length on 10/21/86) (Table 3). However, the humid filtered treatment was lowest for leaf injury on 10/21/86, and the dry filtered treatment was highest for height on 9/23/86.

The only humidity x ozone interactions at the final harvest concerned leaf injury (Table 4). There were many more senescent leaves, greater percentage average leaf injury, and change in percentage leaf injury for the plants exposed to ambient ozone in humid air compared to dry air (Table 5). However, there were no significant humidity x ozone interactions for any biomass, growth, or yield parameters. There was a statistically significant humidity x ozone interaction for height at the 9/23/86 preliminary harvest (Table 2). However, the interaction actually resulted in the greatest height for the ambient air plants with added humidity (Table 3), and there was no evidence for any extra reduction in growth due to ozone in humid air. This effect is observed when lower leaves are lost and plants compensate with extra top growth.

The lack of humidity x ozone effects on yield especially indicates that the predicted tomato losses due to ozone are reasonable for areas of California with different humidity levels during the growing season. There was a trend toward decreased yield (fruit weight) due to humidity itself, which was not statistically significant but which could be factored into models of crop yields based on humidity as well as ozone. These models would more accurately estimate yield than models based solely on ozone effects; however, only the ozone effect would be of direct importance to governmental pollution control agencies. The decreased yield due to humidity may be associated with reduced fruit set as fruit number was actually significantly higher with added humidity while fruit >1 cm diameter was lower with added humidity.

2. Physiological Effects

Important physiological parameters: leaf water potential, stomatal conductance, photosynthesis rate, and transpiration showed periodically significant humidity and/or ozone effects, but no consistently significant interaction between the two stresses (Table 6). The fluorescence data were only taken on a pilot basis on one date. There were no significant differences due to any treatment for any parameter (Table 7). This, coupled with lack of instrumentation for long-term use, resulted in no further measurements.

a. Ozone Effects

Ambient ozone, in general, tended to reduce physiological process rates, which indicated that these plants were under stress compared to filtered air plants (Tables 8-11). Statistically significant effects included more negative water potential on 10/17/86, decreased stomatal conductance and photosynthesis on 9/28/86, and decreased stomatal conductance, photosynthesis, and transpiration on 10/28/86. There also were significant reductions in conductance, photosynthesis, and transpiration when the data were combined across all six measurement dates (Table 6). The decreased physiological process rates likely were related to the decreased growth, yield, and biomass production for the ozone exposed plants compared to filtered air plants.

b. Humidity Effects

Added humidity, in general, increased physiological process rates which likely indicated decreased stress moisture (Tables 8-11). Statistically significant effects included a less negative water potential on 10/17/86, increased photosynthesis and transpiration on 9/18/86, increased stomatal conductance on 9/28/86, increased photosynthesis on 10/14/86, and increased stomatal conductance, photosynthesis, and transpiration on 10/28/86. There also was a decreased transpiration rate with increased humidity on 10/7/86, which was unusual since the associated stomatal conductance actually tended to be higher for humid compared to dry chamber plants on this date. There also were significant increases in conductance and photosynthesis when the data were combined across all six measurement dates (Table 6). The increased physiological process rates likely were related to the increased growth, yield, and biomass production for the ozone exposed plants compared to filtered air plants.

Table 6. Analysis of Variance Results for Effects of Humidity and Ambient Ozone on Tomato Physiology[a]

Parameter	Date	Humidity Effect	Ozone Effect	Humidity x Air Int.	Chamber
Water Potential	9/30/86	NS	*	NS	-[b]
Water Potential	10/17/86	***	NS	NS	NS
Conductance	9/11/86	NS	NS	NS	NS
Conductance	9/18/86	NS	NS	NS	NS
Conductance	9/28/86	***	**	**[c]	NS
Conductance	10/7/86	NS	NS	NS	NS
Conductance	10/14/86	NS	NS	NS	NS
Conductance	10/28/86	***	**	NS	*
Conductance	All Dates	**	**	NS	NS
Photosynthesis	9/11/86	NS	NS	NS	NS
Photosynthesis	9/18/86	*	**	NS	*
Photosynthesis	9/28/86	NS	**	NS	*
Photosynthesis	10/7/86	NS	NS	**[d]	NS
Photosynthesis	10/14/86	*	NS	NS	NS
Photosynthesis	10/28/86	**	***	NS	***
Photosynthesis	All Dates	NS	**	NS	*
Transpiration	9/11/87	NS	NS	NS	NS
Transpiration	9/18/86	**	NS	NS	NS

(continued)

Table 6 (concluded)

Parameter	Date	Humidity Effect	Ozone Effect	Humidity x Air Int.	Chamber
Transpiration	9/28/86	NS	NS	NS	NS
Transpiration	10/7/87	*	NS	*[d]	NS
Transpiration	10/14/87	NS	NS	NS	NS
Transpiration	10/28/86	***	**	NS	***
Transpiration	All Dates	NS	NS	NS	NS
Fluorescence	10/29/86[e]	NS	NS	NS	-
All 24 Parameters[f]		10	9	3	6

[a]Based on analysis of variance with one chamber per treatment and six (water potential) or five (photosynthesis and conductance) plants per chamber. Parameters followed by *, **, and *** are statistically significant at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]No outside measurements.

[c]Greater ozone effect in humidified chamber.

[d]Greater ozone effect in dry chamber.

[e]For all parameters, F_o, F_m, Delta, and Delta/F_m.

[f]Total of 22 parameters for chamber effects.

Table 7. Effects of Humidity and Ambient Ozone on Tomato Chlorophyll Fluorescence Treatment Means[a]

Parameter	Treatment			
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered
Fo	0.58 ± 0.05	0.61 ± 0.08	0.54 ± 0.04	0.63 ± 0.09
Fm	1.02 ± 0.15	2.30 ± 0.46	2.02 ± 0.19	2.35 ± 0.43
Delta	1.44 ± 0.16	1.70 ± 0.19	1.48 ± 0.19	1.72 ± 0.36
Delta/Fm	0.71 ± 0.04	0.73 ± 0.05	0.73 ± 0.04	0.73 ± 0.03

[a]Means ± SD for one chamber per treatment and five plants per chamber.

Table 8. Effects of Humidity and Ambient Ozone on Tomato Water Potential - Treatment Means (in MPa)[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
9/30/86	-0.88 ± 0.08	-0.98 ± 0.09	-0.82 ± 0.11	-0.92 ± 0.15	---
10/17/86	-0.80 ± 0.07	-0.74 ± 0.18	-0.94 ± 0.10	-0.97 ± 0.08	-0.86 ± 0.07

[a]Means ± SD for one chamber per treatment and 6 plants per chamber.

Table 9. Effects of Humidity and Ambient Ozone on Tomato Stomatal Conductance - Treatment Means (cm s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
9/11/86	1.53 ± 0.56	1.52 ± 0.22	1.20 ± 0.18	1.38 ± 0.32	1.16 ± 0.37
9/18/86	2.32 ± 0.25	2.74 ± 0.46	1.27 ± 0.49	2.79 ± 3.15	1.38 ± 0.51
9/28/86	0.48 ± 0.23	1.81 ± 0.41	0.61 ± 0.46	0.80 ± 0.37	0.68 ± 0.40
10/7/86	0.83 ± 0.56	1.33 ± 0.68	0.98 ± 0.53	0.76 ± 0.36	1.12 ± 0.31
10/14/86	0.56 ± 0.90	0.78 ± 0.42	0.28 ± 0.37	0.27 ± 0.16	0.31 ± 0.24
10/28/86	0.92 ± 0.41	1.28 ± 0.38	0.14 ± 0.12	0.39 ± 0.10	0.51 ± 0.31

[a]Mean ± SD for one chamber per treatment and five to eight plants per chamber.

Table 10. Effects of Humidity and Ambient Ozone on Tomato Photosynthesis - Treatment Means (mg CO_2 m^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
9/11/86	1.05 ± 0.36	0.98 ± 0.16	0.90 ± 0.07	0.93 ± 0.19	0.84 ± 0.21
9/18/86	0.93 ± 0.18	1.01 ± 0.26	0.60 ± 0.26	0.95 ± 0.11	0.90 ± 0.13
9/28/86	0.30 ± 0.14	0.59 ± 0.14	0.40 ± 0.17	0.57 ± 0.16	0.61 ± 0.26
10/7/86	0.27 ± 0.19	0.52 ± 0.18	0.60 ± 0.22	0.42 ± 0.15	0.78 ± 0.31
10/14/86	0.39 ± 0.18	0.60 ± 0.16	0.28 ± 0.20	0.36 ± 0.19	0.22 ± 0.24
10/28/86	0.38 ± 0.13	0.64 ± 0.17	0.21 ± 0.11	0.45 ± 0.08	0.61 ± 0.28

[a]Mean ± SD for one chamber per treatment and five to eight plants per chamber.

c. Humidity x Ozone Interactions

There were statistically significant humidity x ozone interactions for only three measurements, and these interactions did not follow any consistent pattern. The highest stomatal conductance on 9/28/86 was in humid/clean chambers, which indicated a possibly greater ozone effect in humid air compared to dry air. The highest photosynthetic rates and transpiration rates on 10/7/86 were in dry/ambient chambers. This would seem to indicate that both humidity and filtered air tended to decrease rates, which is the opposite of what was expected based on the physiological responses to humidity or ozone.

B. Winter Humidity x Sulfur Dioxide Interaction Study

1. Growth and Yield Effects

a. Sulfur Dioxide Effects

Sulfur dioxide reduced growth and biomass production for two of the four species (Table 12). The effects were observed for the following species and parameters: wheat, height and vegetative fresh and dry weights; lettuce, plant diameter and total fresh weight per plant (Tables 13 and 7). No parameter associated with commercial yields was reduced by sulfur dioxide. No significant sulfur dioxide effects were observed for onions or carrots (Tables 15 and 16). The reductions in growth for both wheat and lettuce were similar to results observed in a previous study at UCR (15,21).

b. Humidity Effects

Humidity increased plant growth and yield for three of the four species (Table 12). The effects were observed for the following species and parameters: carrots, average root fresh weights and average total plant fresh weight (Table 15); onions, total plant weight (Table 16); and lettuce, plant diameter and total plant and head fresh weights (Table 14). No significant humidity effects were observed for wheat.

c. Humidity x Sulfur Dioxide Effects

There were statistically significant humidity x sulfur dioxide interactions for all lettuce parameters and for wheat ear weight (Table 12). For both species the interaction consisted of a greater

Table 11. Effects of Humidity and Ambient Ozone on Tomato Transpiration - Treatment Means (mg H_2O m^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
9/11/86	167 ± 44	198 ± 33	175 ± 23	187 ± 30	96 ± 21
9/18/86	256 ± 25	247 ± 22	174 ± 53	228 ± 40	193 ± 54
9/28/86	78 ± 31	159 ± 22	120 ± 69	137 ± 49	126 ± 58
10/7/86	112 ± 66	163 ± 67	249 ± 89	173 ± 59	205 ± 36
10/14/86	79 ± 105	126 ± 43	68 ± 86	86 ± 48	82 ± 42
10/28/86	95 ± 35	130 ± 34	29 ± 22	77 ± 14	98 ± 51

[a]Mean ± SD for one chamber per treatment and five to eight plants per chamber.

Table 12. Analysis of Variance Results for Winter Crops Exposed to Humidity and Sulfur Dioxide[a]

Parameter #	Parameter Name	Humidity Effect	SO_2 Effect	Humidity x SO_2 Interaction	Chamber
			Wheat		
1	# Tillers	NS	NS	NS	NS
2	# Ears	NS	NS	NS	***
3	Height	NS	**	NS	***
4	Veg Fresh Wt	NS	*	NS	***
5	Veg Dry Wt	NS	**	NS	***
6	Ear Wt	NS	NS	*[b]	***
7	Veg Dry/Fr Wt	NS	NS	NS	NS
			Carrots		
1	Fresh Root Wt	NS	NS	NS	NS
2	Fresh Top Wt	NS	NS	NS	***
3	Total Fresh Wt	NS	NS	NS	*
4	Dry Wt Top	NS	NS	NS	NS
5	Av Fresh Root Wt	**	NS	NS	NS
6	Av Fresh Top Wt	NS	NS	NS	**
7	Av Total Fresh W	*	NS	NS	*
8	Av Dry Top Wt	NS	NS	NS	NS
			Onions		
1	Total Fresh Wt	*	NS	NS	***
2	Av Wt/Plant	NS	NS	NS	***

(continued)

Table 12 (concluded) - 2

Parameter #	Parameter Name	Humidity Effect	SO_2 Effect	Humidity x SO_2 Interaction	Chamber
			Lettuce		
1	Plant Diameter	**	**	**[b]	*
2	Total Fresh Wt	***	*	*[b]	**
3	Head Fresh Wt	*	NS	*[b]	*
4	Total Dry Wt	NS	NS	*[b]	NS
			Summary[c]		
1	12 Biomass Param. (# sig)	3	3	2.	8
2	5 Growth Param. (# sig)	1	2	1	3
3	4 Yield Param. (# sig)	2	0	2	3

[a]Based on analysis of variance with three chambers per treatment and three to six pots per chamber. Pots may have replicate plants. Parameters followed by *, **, and *** are significantly different at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]Greatest SO_2 effect in dry chamber.

[c]Number of statistically significant treatment effects. Biomass parameters are weights other than yield. Growth parameters are height, # ears, diameter, tillers, etc. Yield parameters are wheat ear weight, fresh carrot root weight, total onion fresh weight, and lettuce head weight.

Table 13. Effects of Humidity and Sulfur Dioxide on Wheat - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
1	Tillers (#)	44 ± 6	44 ± 6	46 ± 4	48 ± 7	43 ± 8
2	Ear (#)	31 ± 5	28 ± 4	29 ± 5	27 ± 6	10 ± 3
3	Height (m)	0.79 ± 0.04	0.78 ± 0.04	0.80 ± 0.04	0.76 ± 0.04	0.61 ± 0.04
4	Veg Fresh Wt (g)	281 ± 38	245 ± 50	272 ± 46	235 ± 33	170 ± 31
5	Veg Dry Wt (g)	80.7 ± 11.9	66.5 ± 11.5	75.4 ± 9.9	64.4 ± 9.8	47.2 ± 7.9
6	Ear Wt (g)	41.9 ± 14.8	44.1 ± 11.0	49.0 ± 11.1	33.8 ± 8.3	26.0 ± 8.9
7	Veg Dry/Fr	0.29 ± 0.03	0.27 ± 0.02	0.28 ± 0.03	0.27 ± 0.02	0.28 ± 0.03

[a]Means ± SD for three chambers per treatment and five pots per chamber.

Table 14. Effects of Humidity and Sulfur Dioxide on Lettuce - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
1	Plant Diameter (m)	0.38 ± 0.03	0.39 ± 0.03	0.39 ± 0.03	0.33 ± 0.02	0.35 ± 0.02
2	Total Fr Wt (g)	894 ± 131	892 ± 95	836 ± 76	700 ± 65	693 ± 107
3	Head Fr Wt (g)	545 ± 114	580 ± 70	504 ± 103	438 ± 93	381 ± 89
4	Total Dry Wt (g)	50.9 ± 7.7	51.3 ± 6.9	51.6 ± 4.9	42.9 ± 6.5	48.7 ± 7.2

[a]Means ± SD for three chambers per treatment and five pots per chamber.

Table 15. Effects of Humidity and Sulfur Dioxide on Carrots - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
1	Root Fr Wt (g)	471 ± 71	493 ± 69	431 ± 62	441 ± 76	390 ± 72
2	Top Fr Wt (g)	174 ± 32	167 ± 25	185 ± 35	163 ± 22	122 ± 18
3	Total Fr Wt (g)	644 ± 85	661 ± 84	616 ± 68	604 ± 92	511 ± 87
4	Top Dry Wt (g)	27.2 ± 4.8	25.8 ±3.7	28.5 ± 5.9	25.9 ± 2.9	20.8 ± 3.0
5	Av Root Fr Wt (g)	93.4 ± 16.5	97.0 ± 11.5	84.1 ± 12.2	91.8 ± 21.3	75.8 ± 13.3
6	Av Top Fr Wt (g)	34.3 ± 5.8	33.0 ± 5.3	36.4 ± 7.8	30.3 ± 7.3	23.9 ± 3.8
7	Av Total Fr Wt (g)	27.7 ± 19.1	130.0 ± 14.7	120.5 ± 15.2	112.1 ± 27.9	99.6 ± 16.4
8	Av Dry Wt Top (g)	5.8 ± 0.9	5.1 ± 0.7	5.6 ± 1.3	4.8 ± 1.2	4.1 ± 0.7

[a]Means ± SD for three chambers per treatment and five pots per chamber.

Table 16. Effects of Humidity and Sulfur Dioxide on Onions - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
1	Total Fr Wt (g)	417 ± 82	398 ± 55	375 ± 70	356 ± 76	256 ± 32
2	Av Fr Wt (g)	84.4 ± 14.4	87.8 ± 17.0	86.3 ± 15.7	77.9 ± 15.5	54.1 ± 4.8

[a]Means ± SD for three chambers per treatment and five pots per chamber.

sulfur dioxide effect in the dry chamber. The interaction was especially dramatic for lettuce where head fresh weight was decreased 13% by sulfur dioxide in dry chambers, whereas weight was increased 6% by sulfur dioxide in humid chambers (Table 14).

These results suggest that the sensitivity of plants to sulfur dioxide actually was reduced with added humidity. However, this reduced sensitivity is uncertain due to the difficulty in accurately assigning sulfur dioxide concentrations to the humid chambers. As indicated in Table 1, the sulfur dioxide concentration measured 20% higher in the dry chambers than in the ambient chambers. There is evidence that this 20% was not real as the flow of sulfur dioxide into humid and ambient chambers was the same and, thus, the concentration inside the chambers should have been similar. Instead, it is likely that there was loss of sulfur dioxide to the Teflon sampling lines before the samples reached the analyzer. The presence of added water vapor in the air, especially during the cooler winter months, would have resulted in the absorption of sulfur dioxide.

Even if the 20% greater sulfur dioxide concentration in dry chambers compared to humid chambers was real, this increased concentration by itself would not necessarily produce the large difference in plant response. Furthermore, as discussed below, there is limited stomatal conductance evidence that suggests that the actual sulfur dioxide uptake was greater for humid chamber plants.

2. Physiological Effects

The results from the analysis of variance of physiological data for winter crops are shown in Table 17. The measurements focused on water vapor exchange rates, primarily for wheat. There also were limited measurements for lettuce and onions.

a. Sulfur Dioxide Effects

Sulfur dioxide caused a statistically significant increase in stomatal conductance and transpiration for wheat on 1/22/87 and onions on 1/13/87 (Tables 17-19). There also was a trend (but not statistically significant) for increased conductance with sulfur dioxide exposure with some other measurements such as lettuce on 1/13/87. Increases in stomatal conductance with sulfur dioxide exposure have been reported for other species in laboratory experiments (2,16), but generally have not been reported with field studies (3).

Table 17. Analysis of Variance Results for Effects of Humidity and Sulfur Dioxide on Winter Crop Physiology[a]

Parameter	Date	Humidity Effect	SO_2 Effect	Humidity x SO_2 Int.	Chamber Effect
		Wheat			
Conductance	1/13/87	**	NS	NS	-[b]
Conductance	1/14/87	NS	NS	NS	NS
Conductance	1/22/87	***	*	*[c]	NS
Conductance	1/26/87	NS	NS	NS	NS
Transpiration	1/13/87	NS	NS	NS	NS
Transpiration	1/14/87	NS	NS	NS	-
Transpiration	1/22/87	**	*	*[c]	NS
Transpiration	1/26/87	NS	NS	NS	NS
		Lettuce			
Conductance	1/13/87	NS	NS	NS	-
Conductance	1/14/87	NS	NS	NS	-
Conductance	1/22/87	***	NS	*[d]	NS
Transpiration	1/13/87	NS	NS	NS	-
Transpiration	1/14/87	NS	NS	NS	NS
Transpiration	1/22/87	***	NS	**[d]	**
		Onions			
Conductance	1/13/87	*	*	NS	NS
Transpiration	1/13/87	*	**	NS	-
16 Parameters	All dates	7	4	4	1[e]

[a]Based on analysis of variance with three chambers per treatment and five plants per chamber. Parameters followed by *, **, and *** are statistically significant at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]No data.

[c]Greatest transpiration in humid SO_2 chambers, lowest in dry ambient chambers.

[d]Greatest value in humid SO_2 chambers, lowest in dry SO_2 chambers.

[e]Outside plots measured for 10 parameters.

Table 18. Effects of Humidity and SO_2 on Winter Crop Transpiration - Treatment Means (in mg H_2O mg cm^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
			Wheat		
1/13/87	2.15 ± 1.24	3.79 ± 0.21	2.66 ± 0.23	2.34 ± 0.20	-
1/14/87	5.77 ± 1.34	4.88 ± 2.09	3.76 ± 0.80	3.27 ± 1.64	-
1/22/87	4.15 ± 1.49	6.05 ± 1.77	3.34 ± 1.43	3.90 ± 1.33	2.87 ± 1.06
1/26/87	4.29 ± 2.62	4.30 ± 3.00	4.70 ± 2.50	2.79 ± 1.51	4.41 ± 2.27
			Lettuce		
1/13/87	1.75 ± 0.79	2.52 ± 0.55	1.20 ± 0.16	2.33 ± 0.48	-
1/14/87	3.82 ± 0.83	5.90 ± 8.92	3.35 ± 0.53	2.98 ± 2.14	-
1/22/87	3.37 ± 0.99	3.83 ± 0.92	3.03 ± 0.50	2.16 ± 0.50	1.67 ± 0.66
			Onions		
1/13/87	2.06 ± 1.10	4.03 ± 0.69	1.11 ± 0.46	2.93 ± 0.93	-

[a]Means ± SD for three chambers per treatment three to five plants per chamber.

Table 19. Effects of Humidity and SO_2 on Winter Crop Stomatal Conductance - Treatment Means (in cm s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid SO_2	Dry Ambient	Dry SO_2	Dry Outside
			Wheat		
1/13/87	0.37 ± 0.11	0.38 ± 0.03	0.26 ± 0.03	0.17 ± 0.02	-
1/14/87	0.63 ± 0.14	0.47 ± 0.19	0.26 ± 0.06	0.24 ± 0.12	-
1/22/87	0.39 ± 0.14	0.57 ± 0.18	0.16 ± 0.08	0.25 ± 0.09	0.21 ± 0.10
1/26/87	0.28 ± 0.18	0.34 ± 0.25	0.20 ± 0.09	0.14 ± 0.08	0.23 ± 0.14
			Lettuce		
1/13/87	0.21 ± 0.10	0.26 ± 0.06	0.11 ± 0.02	0.16 ± 0.04	-
1/14/87	0.34 ± 0.06	0.27 ± 0.11	0.23 ± 0.04	0.18 ± 0.06	-
1/22/87	0.30 ± 0.09	0.34 ± 0.08	0.15 ± 0.03	0.13 ± 0.03	0.13 ± 0.05
			Onions		
1/13/87	0.24 ± 0.15	0.41 ± 0.09	0.08 ± 0.01	0.23 ± 0.08	-

[a]Means ± SD for three chambers per treatment and three to five plants per chamber.

b. Humidity Effects

There was a general increase in stomatal conductance and transpiration across all measurement dates for all three species (Tables 17-19). The increases were statistically significant for both stomatal conductance and transpiration for wheat and lettuce on 1/22/87 and for onions on 1/13/87.

The higher conductance in humid vs. dry chambers should have resulted in a proportionally higher flux of sulfur dioxide into leaves of humid chamber plants, as flux of sulfur dioxide is primarily controlled by stomatal conductance (11). Higher sulfur dioxide flux in turn should have resulted in greater effects to the plants exposed to sulfur dioxide in the humid compared to ambient chambers, however, this did not occur. Furthermore, if the increased conductance in humid chambers persisted on all exposure days, the subsequent large increase would have more than compensated for any lower sulfur dioxide concentration in the humid vs. dry chambers (Table 1).

c. Humidity x Sulfur Dioxide Interactions

There were statistically significant interactions between sulfur dioxide and humidity on stomatal conductance and transpiration for both wheat and lettuce on 1/22/87 (Tables 17-19). For lettuce, the highest conductance and transpiration values were for humid/sulfur dioxide plants while the lowest values were for dry/sulfur dioxide plants. For wheat, the highest values were for humid/sulfur dioxide plants while the lowest values were for dry/ambient plants. Evidentally, humidity and sulfur dioxide acted upon stomata synergistically to provide maximum stomatal opening.

C. Spring Humidity x Ozone Interaction Study

1. Injury, Growth, and Yield Effects

a. Ozone Effects

Ambient ozone produced considerable leaf injury on almonds, beans, and melons. The symptoms consisted of a general chlorosis on almonds and melons, and a chlorosis with necrotic lesions and bronzing on beans. There was some tip die back and other injury symptoms observed on the ponderosa pine and Douglas fir; these symptoms could possibly be attributed to ambient ozone. However, the injury to Douglas fir could

also have been related to heat stress. Many of the Douglas fir seedlings did not grow rapidly, and a number died during the growing season. This likely was due to the lack of adaptation of Douglas fir to hot, dry summers as occurring in Riverside, compared to the cooler more humid summers in northern California. The injury to almonds and beans was quantified with results from the statistical analysis (Table 20). Results from the statistical analysis of injury rating for ponderosa pine and Douglas fir also are included; however, these results should be approached with caution as the injury was rated only on a 1 (injury present) or 0 (no injury) basis.

There was a significantly lower number of healthy leaves and percentage injured leaves for almonds growing in ambient air compared to filtered air (Table 21).

Ozone had a significant effect on growth and yield for both groups of beans (Table 20). For group one, fresh and dry weights of beans from the first pick were reduced by ozone (Table 22). For group two, all yield and growth responses were reduced by ozone except for dry weight per bean (Table 23). Growth of almonds and melons was not significantly affected by ozone in this study. However, there were limitations with both species which do not permit the possibility of potential ozone effects to be ruled out entirely. For almonds, all leaves were already on the trees prior to beginning of exposure in June. Thus, the two months of exposure may not have been adequate to affect growth and biomass which was largely determined before the study began. For melons, approximately one month of exposure for this study was not adequate to determine effects on yield; few had been set by the end of the study, so it was not possible to determine effects on yield (Table 24). Ozone had no statistically significant effects on ponderosa pine or Douglas fir (Tables 25 and 26).

b. Humidity Effects

Humidity significantly affected beans, almonds, and melons (Table 20). Almond trees had more injured leaves and a smaller trunk diameter in humid chambers compared to dry chambers (Table 21).

Beans showed significant growth, yield, and injury responses to added humidity (Table 20). The humidity effects occurred for both groups (plantings) of beans, as well as for nearly all response parameters. For beans in group one harvested at the first pick, the total fresh and dry

Table 20. Analysis of Variance Results for Spring Crops Exposed to Humidity a Ambient Air (Ozone)[a]

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamb Effec
		Almonds			
1	# Healthy Leaves	NS	***	*[b]	NS
2	# Nodes	NS	NS	NS	NS
3	% Injured Leaves	***	***	***[b]	**
4	% DW/FW Leaves	NS	NS	NS	NS
5	Fresh Wt Total Wood	NS	NS	NS	NS
6	% FW/DW Biomass	NS	NS	NS	NS
7	Fresh Wt Leaves	NS	NS	NS	NS
8	Fresh Wt Branches	NS	NS	NS	NS
9	Fresh Wt Trunk	NS	NS	NS	NS
10	Tree Height	NS	NS	NS	NS
11	Trunk Diameter	*	NS	NS	NS
12	Dry Wt Leaves	NS	NS	NS	NS
13	Dry Wt Branches	NS	NS	NS	NS
14	Dry Wt Trunk	NS	NS	NS	NS
		Beans, Group One			
	First Pick				
1	# Beans	NS	NS	NS	NS
2	Beans Fresh Wt	*	**	NS	NS
3	Beans Dry Wt	*	**	NS	NS

(continued)

Table 20 (continued) - 2

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamber Effect
4	DW/FW of Beans	**	NS	NS	*
5	Fresh Wt/Beans	NS	NS	NS	NS
	Second Pick				
1	# Beans	**	NS	NS	NS
	Beans, Group Two[c]				
1	Leaf Injury	**	***	**[b]	--[d]
2	# Beans	***	***	NS	NS
3	Fresh Wt Beans	***	***	NS	NS
4	Dry Wt Beans	***	***	NS	*
5	Fresh Wt Plant	***	***	***[b]	NS
6	Dry Wt Plant	***	***	***[b]	NS
7	Fresh Wt/Bean	**	*	NS	NS
8	Dry Wt/Bean	*	NS	NS	**
9	Fresh Biomass	**	***	*[b]	NS
10	Dry Biomass	**	***	**[b]	NS
11	Dry/Fresh Biomass	NS	**	NS	**

(continued)

Table 20 (continued) - 3

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamber Effect
		Melons			
1	Total Vine Length	***	NS	NS	--[d]
2	Number of Flowers	NS	NS	NS	--
3	Number of Fruit	NS	NS	NS	--
		Ponderosa Pine			
1	Fresh Wt, Old Wood	NS	NS	NS	NS
2	Fresh Wt, New Wood	NS	NS	NS	NS
3	Total Fresh Wt	NS	NS	NS	NS
4	Ratio New/Old Fresh (%)	NS	NS	NS	NS
5	Injury	NS	NS	*	NS
6	Dry Wt, Old Wood	NS	NS	NS	NS
7	Dry Wt, New Wood	NS	NS	NS	NS
8	Total Dry Wt	NS	NS	NS	NS
9	Ratio New/Old Dry (%)	NS	NS	NS	NS
		Douglas Fir			
1	Fresh Wt, Old Wood	NS	NS	NS	NS
2	Fresh Wt, New Wood	NS	NS	NS	NS
3	Total Fresh Wt	NS	NS	NS	NS
4	Ratio New/Old Fresh (%)	NS	NS	NS	NS

(continued)

Table 20 (continued) - 4

Parameter #	Parameter Name	Humidity Effect	Air Effect	Humidity x Air Int.	Chamber Effect
5	Injury	NS	NS	NS	NS
6	Dry Wt, Old Wood	NS	NS	NS	NS
7	Dry Wt, New Wood	NS	NS	NS	NS
8	Total Dry Wt	NS	NS	NS	NS
9	Ratio New/Old Dry (%)	NS	NS	NS	NS
10	Height				
	Summary				
	30 Biomass Param. (# sig)	4	5	4	1
	5 Growth Param. (# sig)	2	0	0	0
	13 Yield Param. (# sig)	9	6	0	3
	5 Injury Param. (# sig)	2	3	4	1

[a]Based on analysis of variance with three chambers per treatment and five plants per chamber. Parameters followed by *, **, and *** are significantly different at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]Greatest ozone effect in humid chamber.

[c]Across all cultivars of beans.

[d]Not measured.

[e]Number of statistically significant treatment effects. Biomass parameters are all weights. Growth parameters are height, diameter, numbers, etc. Yield parameters are numbers and weights for beans and, flowers and fruit for melons. Injury parameters are numbers and percentage healthy leaves.

Table 21. Effects of Humidity and Ozone on Almonds - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
1	Healthy Lv (#)	85 ± 11	126 ± 15	105 ± 10	119 ± 19	103 ± 9
2	Nodes (#)	149 ± 14	136 ± 17	136 ± 9	130 ± 21	140 ± 11
3	Injured Lv (%)	43 ± 5	8 ± 2	22 ± 4	8 ± 4	27 ± 3
4	Lf Dry/Fr Wt (%)	39 ± 9	43 ± 10	39 ± 2	36 ± 3	42 ± 3
5	FW Total Wood (g)	621 ± 154	618 ± 170	682 ± 138	673 ± 168	768 ± 168
6	Biomass Fr/Dry	2.04 ± 0.12	1.96 ± 0.16	2.00 ± 0.10	2.02 ± 0.16	1.95 ± 0.18
7	Leaf FW (g)	283 ± 59	306 ± 71	297 ± 52	326 ± 89	322 ± 66
8	Branch FW (g)	338 ± 101	312 ± 110	385 ± 91	348 ± 97	446 ± 108
9	Trunk FW (g)	309 ± 68	298 ± 56	328 ± 50	332 ± 64	319 ± 53
10	Height (m)	1.59 ± 0.19	1.50 ± 0.17	1.53 ± 0.13	1.55 ± 0.11	1.64 ± 0.15
11	Trunk Dia (cm)	22 ± 2	23 ± 2	24 ± 2	24 ± 2	25 ± 1
12	Leaf DW (g)	106 ± 23	127 ± 24	116 ± 30	116 ± 30	136 ± 27
13	Branch DW (g)	172 ± 52	164 ± 56	199 ± 51	186 ± 46	233 ± 76
14	Trunk DW (g)	178 ± 39	176 ± 33	190 ± 26	193 ± 38	193 ± 28

[a]Means ± SD for three chambers per treatment and five plants per chamber.

Table 22. Effects of Humidity and Ozone on Beans, Group One - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
			First Pick			
1	Beans (#)	24 ± 10	41 ± 21	28 ± 9	54 ± 19	34 ± 11
2	Beans FW (g)	65 ± 33	134 ± 83	100 ± 99	216 ± 80	108 ± 39
3	Beans DW (g)	11 ± 6	24 ± 16	21 ± 6	48 ± 21	20 ± 7
4	Beans D/F Wt (%)	16 ± 2	18 ± 4	26 ± 7	22 ± 3	18 ± 4
5	Beans FW (g)	2.7 ± 0.7	3.1 ± 1.0	3.3 ± 2.0	4.0 ± 0.9	2.8 ± 0.9
			Second Pick			
6	Beans (#)	26 ± 20	39 ± 31	8 ± 7	11 ± 13	8 ± 8

[a]Mean ± SD for three chambers per treatment, with two cultivars and three plants per cultivar per chamber. There was no significant cultivar response except for number of beans, first pick, so the data are averaged across both cultivars.

Table 23. Effects of Humidity and Ozone on Beans, Group Two - Treatment Means for Three Cultivars[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
		Great Northern (Tolerant)				
1	Leaf Injury (%)	40 ± 8	0	24 ± 5	0	--
2	Beans (#)	36 ± 13	59 ± 40	57 ± 13	92 ± 30	64 ± 22
3	Beans FW (g)	101 ± 49	191 ± 140	208 ± 62	332 ± 102	246 ± 65
4	Beans DW (g)	17 ± 10	34 ± 26	33 ± 12	62 ± 22	53 ± 11
5	Plant FW (g)	147 ± 35	201 ± 67	135 ± 25	130 ± 38	115 ± 35
6	Plant DW (g)	35 ± 7	57 ± 19	32 ± 9	32 ± 9	26 ± 8
7	FW/Bean (g)	2.8 ± 0.4	3.0 ± 0.7	3.6 ± 0.5	3.6 ± 0.2	4.0 ± 0.5
8	DW/Bean (g)	0.5 ± 0.1	0.5 ± 0.2	0.6 ± 0.1	0.7 ± 0.1	0.9 ± 0.3
9	Biomass FW (g)	248 ± 29	391 ± 172	343 ± 67	462 ± 105	360 ± 67
10	Biomass DW (g)	52 ± 8	91 ± 35	65 ± 12	95 ± 21	79 ± 11
11	Biomass D/F Wt (%)	21 ± 2	24 ± 5	19 ± 2	21 ± 2	22 ± 3
		Great Northern (Susceptible)				
1	Leaf Injury (%)	82 ± 13	0	51 ± 9	0	--
2	Beans (#)	57 ± 10	82 ± 28	88 ± 14	109 ± 14	72 ± 24
3	Beans FW (g)	131 ± 35	251 ± 108	257 ± 45	382 ± 39	224 ± 74
4	Beans DW (g)	18 ± 5	36 ± 14	37 ± 9	66 ± 7	37 ± 12
5	Plant FW (g)	73 ± 31	163 ± 31	56 ± 25	96 ± 33	76 ± 32
6	Plant DW (g)	14 ± 6	34 ± 7	11 ± 5	20 ± 5	15 ± 6

(continued)

Table 23 (concluded) - 2

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
7	FW/Bean (g)	2.4 ± 0.5	3.0 ± 0.5	2.9 ± 0.2	3.5 ± 0.2	3.2 ± 0.7
8	DW/Bean (g)	0.3 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.6 ± 0.0	0.6 ± 0.2
9	Biomass FW (g)	203 ± 62	414 ± 101	313 ± 59	478 ± 42	300 ± 94
10	Biomass DW (g)	32 ± 10	70 ± 15	49 ± 13	86 ± 7	53 ± 17
11	Biomass D/F Wt (%)	15 ± 1	17 ± 2	15 ± 2	18 ± 1	18 ± 3
			Pinto			
1	Leaf Injury (%)	51 ± 9	0	33 ± 6	0	--
2	Beans (#)	22 ± 14	64 ± 14	55 ± 12	79 ± 31	49 ± 22
3	Beans FW (g)	62 ± 46	230 ± 61	224 ± 51	355 ± 148	236 ± 107
4	Beans DW (g)	8 ± 7	37 ± 17	36 ± 11	61 ± 23	49 ± 22
5	Plant FW (g)	100 ± 26	256 ± 87	141 ± 46	104 ± 30	112 ± 49
6	Plant DW (g)	22 ± 7	58 ± 22	33 ± 8	25 ± 6	25 ± 10
7	FW/Bean (g)	2.7 ± 0.9	3.8 ± 0.8	4.1 ± 0.3	4.4 ± 0.7	5.0 ± 1.0
8	DW/Bean (g)	0.4 ± 0.3	0.6 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	1.1 ± 0.3
9	Biomass FW (g)	163 ± 57	485 ± 75	365 ± 30	459 ± 159	348 ± 148
10	Biomass DW (g)	30 ± 11	95 ± 13	69 ± 11	86 ± 25	75 ± 31
11	Biomass D/F Wt (%)	19 ± 3	20 ± 2	19 ± 3	19 ± 2	22 ± 2

[a]Mean ± SD for three chambers per treatment, with three plants per cultivar per chamber.

[b]Statistical analysis on arcsin transformed data. Not measured for outside plants.

Table 24. Effects of Humidity and Ozone on Melons - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered
1	Vine Length (m)	2.44 ± 46	2.14 ± 0.46	0.96 ± 0.21	0.98 ± 0.23
2	Flowers (#)	13 ± 10	12 ± 5	3 ± 2	4 ± 3
3	Fruit (#)	0.8 ± 0.8	0.7 ± 0.8	0.8 ± 0.9	0.9 ± 0.9

[a]Mean ± SD for three chambers per treatment, five plants per chamber. Dry chamber plants harvested one week after humid chamber plants.

Table 25. Effects of Humidity and Ozone on Ponderosa Pine - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
1	Old Wood Fr Wt (g)	44 ± 21	35 ± 17	39 ± 12	40 ± 13	43 ± 23
2	New Wood Fr Wt (g)	42 ± 22	40 ± 21	40 ± 11	41 ± 14	43 ± 26
3	Total Wood Fr Wt (g)	86 ± 35	75 ± 34	78 ± 21	81 ± 24	85 ± 47
4	New/Old Fr Wt (%)	48 ± 13	50 ± 18	51 ± 7	71 ± 9	43 ± 21
5	Injury (%)	0.8 ± 0.4	0.7 ± 0.5	0.9 ± 0.4	0.4 ± 0.5	0.6 ± 0.4
6	Old Wood Dry Wt (g)	17 ± 7	16 ± 5	15 ± 5	17 ± 5	17 ± 8
7	New Wood Dry Wt (g)	14 ± 7	13 ± 7	13 ± 4	15 ± 6	15 ± 10
8	Total Wood Dry Wt (g)	31 ± 13	30 ± 10	28 ± 8	32 ± 10	32 ± 17
9	New Old/ Dry Wt (%)	44 ± 10	43 ± 16	47 ± 7	47 ± 9	41 ± 20

[a]Mean ± SD for three chambers per treatment, four or five plants per chamber.

[b]Plants rated as 1 - with injury, 0 - without injury.

Table 26. Effects of Humidity and Ozone on Douglas Fir - Treatment Means[a]

Parameter #	Parameter Name	Treatment: Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
1	Old Wood Fr Wt (g)	31 ± 10	23 ± 13	24 ± 9	24 ± 9	17 ± 10
2	New Wood Fr Wt (g)	24 ± 10	18 ± 12	23 ± 16	15 ± 6	13 ± 9
3	Total Wood Fr Wt (g)	55 ± 19	41 ± 24	47 ± 23	39 ± 15	31 ± 18
4	New/Old Fr Wt (%)	42 ± 9	42 ± 8	46 ± 8	39 ± 4	42 ± 6
5	Injury (%)	0.5 ± 0.5	0.3 ± 0.5	0.4 ± 0.5	0.6 ± 0.5	0.3 ± 0.5
6	Old Wood Dry Wt (g)	13 ± 4	10 ± 5	10 ± 4	10 ± 4	8 ± 4
7	New Wood Dry Wt (g)	9 ± 4	7 ± 5	7 ± 4	6 ± 2	5 ± 4
8	Total Wood Dry Wt (g)	22 ± 7	18 ± 9	16 ± 8	16 ± 6	13 ± 8
9	New Old/ Dry Wt (%)	41 ± 9	40 ± 8	36 ± 15	37 ± 5	36 ± 14
10	Height (m)	0.42 ± 0.08	0.39 ± 0.08	0.37 ± 0.07	0.38 ± 0.04	0.33 ± 0.08

[a]Mean ± SD for three chambers per treatment, three to five plants per chamber for a total of 10 to 15 plants per treatment.

[b]Plants rated as 1 - with injury, 0 - without injury.

weights were lower, and the dry/fresh weight ratio was higher in the humid than in the dry chambers (Table 22). However, the number of beans and fresh weight per bean were not statistically significant. For beans in group one harvested at the second pick, the number of beans per plant was higher in the humid chambers than in the dry chambers. Beans in group two showed increased leaf injury and decreased yield in humid vs. dry chambers (Table 20). Yield was depressed by higher humidity for all parameters, i.e., number of beans, total fresh and dry weight of beans per plant, and fresh and dry weight per bean (Table 23). In contrast, growth parameters were higher in humid chambers than in dry chambers (fresh and dry weight of vegetative plant parts). Thus, for beans in group two, the net result of added humidity was a reduced dry biomass, as the contribution of fruit to the total weight was greater than the contribution of vegetative plant.

Increased humidity resulted in increased vegetative growth for melons (vine length and number of flowers, Table 24). The effect of humidity on fruit could not really be determined as there was only an average of one fruit per plant.

Increased humidity had no effect on injury, growth, or biomass production of ponderosa pine or Douglas fir (Table 20). As shown by the data for ponderosa pine (Table 26) and Douglas fir (Table 27), there was little variation in response to humidity between treatments. Evidently, the fact that the number of leaves and amount of wood on these trees was essentially determined earlier (before the study began), resulted in little opportunity for the ozone to affect the responses.

c. Humidity x Ozone Interactions

There were very few significant interactions between humidity and ambient ozone; added humidity significantly increased visible injury from ozone for both almonds and beans (Table 20). Humidity also affected the percentage dry/fresh weight for almond leaves, with a reduced percentage with ozone in humid chambers, but an increased percentage in dry chambers (Table 21). For the second group of beans, the highest fresh and dry weights for vegetative parts of the plant were in the filtered humid chambers, whereas the highest total biomass fresh and dry weights were in the filtered dry chambers (Table 23). There were no interactions for the first group of beans, melons, or Douglas fir. There was a significant interaction for leaf injury to ponderosa pine, with the most

injury in humid ambient air and least injury in dry clean air. However, the importance of this interaction was questionable, as there were no significant individual air or humidity treatment effects.

d. Bean Cultivar Effects

For group one, the only significant cultivar effects were a greater number of beans for the susceptible than the tolerant cultivar, both at the first and second picks (Table 27). There were no significant cultivar x treatment interactions. For group two, the three bean cultivars generally differed in response to humidity and ozone (Table 27). In general, the susceptible Great Northern strain had greater yields and vegetative growth and biomass production than either the tolerant strain or pinto beans (Tables 23 and 25). The exception was for fresh weight/bean where pinto > Great Northern tolerant > Great Northern susceptible. Cultivar x humidity or ozone treatment interactions were: greatest injury for susceptible plants in humid ambient chambers, greatest number of beans for tolerant dry filtered chamber, and greatest fresh weight/bean for humid pinto plants.

2. Physiological Effects

a. Ozone Effects

There was a trend toward reduced stomatal conductance and transpiration for almonds exposed to ozone, but the differences between filtered and ambient chambers were statistically significant only for conductance and transpiration on 6/24/87 and just transpiration on 5/12/87 (Tables 28-30). In contrast, bean stomatal conductance was reduced significantly on four of the seven measurement days (Tables 28, 31, and 32), and transpiration was reduced by ozone on one day (Tables 28, 33, and 34). The differences in stomatal response between the two species are likely due to greater sensitivity of bean leaf cells to ozone, and not differences in ozone uptake (23). The uptake of ozone should have been the same for beans and almonds as the stomatal conductances in filtered air were similar for both species.

b. Humidity Effects

Humidity caused an increased stomatal conductance for both almonds and beans on each measurement date as indicated by the comparison between humidified and dry chambers (Tables 28, 29, 31, and 32).

Table 27. Analysis of Variance for Second Group of Beans Exposed to Humidity and Ambient Air (Ozone) - Cultivar and Cultivar x Air or Humidity Interactions[a]

#	Parameter	Cultivar[b]	Cultivar x Treatment Interactions
		First Group[a]	
1	# Beans	*	NS
2	Beans Fresh Wt	NS	NS
3	Beans Dry Wt	NS	NS
4	DW/FW Beans	NS	NS
5	Fresh Wt/Bean	NS	NS
		Second Group[b]	
1	Leaf Injury	***	***[d]
2	# Beans	***	***[e]
3	Fresh Wt Beans	NS	NS
4	Dry Wt Beans	NS	NS
5	Fresh Wt Plant	***	NS
6	Dry Wt Plant	***	NS
7	Fresh Wt/Bean	***[f]	**[g]
8	Dry Wt/Bean	***	NS
9	Fresh Biomass	NS	NS
10	Dry Biomass	***	NS
11	Dry/Fresh Biomass	***	NS

[a]Based on analysis of variance with three chamber plots per treatment and five plants per chamber. Parameters followed by *, **, and *** are significantly different at $p < 0.05$, 0.01, and 0.005 levels, respectively.

[b]Susceptible > tolerant.

[c]The significant difference is between tolerant or pinto and the susceptible cultivar except for fresh weight/bean.

[d]The significant interactions were for cultivar x air, cultivar x humidity and cultivar x air x humidity.

[e]The significant difference was for cultivar x chamber effect.

[f]There were significant differences among all three cultivars.

[g]The significant interactions were for cultivar x humidity, and cultivar x air.

Table 28. Analysis of Variance Results for Effects of Humidity and Ambient Ozone on Spring Crop Physiology[a]

Parameter	Date	Humidity Effect	Ozone Effect	Humidity x Air Int.	Chamber Effect
		Almonds			
Conductance	5/12/87	***	NS	*	NS
Conductance	6/9/87	***	NS	NS	NS
Conductance	6/10/87	**	NS	*	NS
Conductance	6/24/87	***	**	NS	**
Conductance	6/26/87	***	NS	NS	NS
Conductance	7/14/87	***	NS	NS	NS
Transpiration	5/12/87	*	*	NS	NS
Transpiration	6/9/87	NS	NS	NS	NS
Transpiration	6/10/87	NS	NS	NS	NS
Transpiration	6/24/87	*	*	NS	*
Transpiration	6/26/87	**	NS	NS	NS
Transpiration	7/14/87	***	NS	NS	NS
		Beans			
Conductance	6/9/87	***	*	NS	*
Conductance	6/10/87	***	*	NS	NS
Conductance	6/16/87	***	NS	*	NS
Conductance	6/23/87	***	**	NS	NS
Conductance	6/24/87	***	*	NS	NS
Conductance	7/1/87	***	NS	NS	NS
Conductance	7/7/87	***	NS	NS	NS
Transpiration	6/9/87	***	*	NS	**
Transpiration	6/10/87	NS	NS	NS	NS
Transpiration	6/16/87	**	NS	**	NS
Transpiration	6/23/87	NS	NS	NS	NS
Transpiration	6/24/87	*	NS	NS	NS
Transpiration	7/1/87	NS	NS	NS	NS

(continued)

Table 28 (concluded) - 2

Parameter	Date	Humidity Effect	Ozone Effect	Humidity x Air Int.	Chamber Effect
Transpiration	7/7/87	**	NS	NS	NS
26 Parameters	All Dates	21	8	4	4

[a]Based on analysis of variance with three chambers per treatment and variable plants per chamber measured for a total of four to nine plants per treatment. The results for 6/9/87, 6/10/87, and 6/16/87 are across three cultivars as there were generally too few plants per cultivar (one to three) for detection of treatment differences. The results for 6/23/87, 6/24/87, 7/1/87, and 7/7/87 are only for pinto beans as this was the only cultivar measured. Parameters followed by *, **, and *** are statistically significant at $p < 0.05$, 0.01, and 0.005 levels, respectively.

Table 29. Effects of Humidity and Ambient Ozone on Almond Stomatal Conductance - Treatment Means (cm s^{-1} except for μg m^{-2} s^{-1} on 6/24/87 and 6/26/87)[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
5/12/87	1.27 ± 0.31	1.20 ± 0.21	0.82 ± 0.19	1.10 ± 0.08	0.78 ± 0.15
6/9/87	1.49 ± 0.19	1.53 ± 0.07	1.15 ± 0.16	1.21 ± 0.21	1.10 ± 0.06
6/10/87	1.25 ± 0.04	1.44 ± 0.20	1.11 ± 0.19	0.96 ± 0.09	1.18 ± 0.06
6/24/87	418 ± 80	458 ± 72	272 ± 82	354 ± 93	374 ± 62
6/26/87	417 ± 49	406 ± 50	296 ± 66	336 ± 49	321 ± 51
7/14/87	1.01 ± 0.44	1.18 ± 0.17	0.51 ± 0.20	0.49 ± 0.11	0.37 ± 0.11

[a]Mean ± SD for a total of two to nine plants per treatment from one to three chambers.

Table 30. Effects of Humidity and Ambient Ozone on Almond Transpiration - Treatment Means (μg H_2O cm^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
5/12/87	23.7 ± 3.3	24.0 ± 2.9	18.2 ± 2.9	23.9 ± 3.1	20.2 ± 2.0
6/9/87	18.1 ± 2.8	17.4 ± 5.5	19.1 ± 1.1	17.1 ± 1.8	21.7 ± 3.3
6/10/87	18.6 ± 0.5	18.3 ± 2.1	19.4 ± 2.1	16.5 ± 1.7	19.4 ± 0.2
6/24/87	10.4 ± 1.4	11.6 ± 1.3	9.1 ± 2.2	10.6 ± 2.3	11.2 ± 1.1
6/26/87	11.5 ± 1.2	11.5 ± 1.5	9.6 ± 1.8	10.7 ± 1.2	10.7 ± 1.5
7/14/87	19.6 ± 6.8	22.4 ± 4.8	13.5 ± 4.2	12.3 ± 4.0	10.7 ± 2.5

[a]Mean ± SD for a total of two to nine plants from one to three chambers per treatment.

Table 31. Effects of Humidity and Ambient Ozone on Bean Stomatal Conductance - Treatment Means for Three Cultivars (cm s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
			Great Northern (Tolerant)		
6/9/87	1.49 ± 0.27	1.52 ± 0.22	---	1.20 ± 0.12	1.12 ± 0.17
6/10/87	1.47 ± 0.25	1.44 ± 0.07	0.94 ± 0.22	1.06 ± 0.04	0.86 ± 0.21
6/16/87	1.04 ± 0.36	1.40 ± 0.38	0.60 ± 0.24	0.67 ± 0.18	0.21 ± 0.15
			Great Northern (Susceptible)		
6/9/87	1.50 ± 0.21	1.48 ± 0.09	0.63 ± 0.03	1.09 ± 0.27	0.99
6/10/87	1.28 ± 0.18	1.61 ± 0.28	0.80	0.92 ± 0.15	0.71 ± 0.09
6/16/87	1.01 ± 0.11	1.48 ± 0.19	0.49 ± 0.17	0.67 ± 0.18	0.21 ± 0.29
			Pinto		
6/9/87	1.40 ± 0.04	1.76 ± 0.10	0.95 ± 0.01	1.18 ± 0.13	0.94 ± 0.16
6/10/87	1.43 ± 0.27	1.52 ± 0.20	0.69 ± 0.45	0.91 ± 0.15	0.91 ± 0.08
6/16/87	0.54 ± 0.69	1.02 ± 0.24	0.37 ± 0.11	0.54 ± 0.25	0.55 ± 0.09

[a]Mean ± SD for one or two chambers per treatment and one or three plants per cultivar per chamber, for a total of from one to 17 plants per treatment.

Table 32. Effects of Humidity and Ambient Ozone on Stomatal Conductance - Treatment Means for Pinto Beans (μmol m^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
6/23/87	440 ± 237	604 ± 95	232 ± 82	326 ± 186	272 ± 198
6/24/87	362 ± 209	504 ± 128	204 ± 55	278 ± 125	290 ± 121
7/1/87	288 ± 133	375 ± 61	204 ± 62	203 ± 63	209 ± 78
7/7/87	300 ± 111	351 ± 35	193 ± 73	205 ± 47	215 ± 70

[a]Mean ± SD for three chambers per treatment and three plants per cultivar per chamber.

Table 33. Effects of Humidity and Ambient Ozone on Bean Transpiration - Treatment Means for Three Cultivars (mg H_2O m^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
			Great Northern (Tolerant)		
6/9/87	19.4 ± 2.6	19.6 ± 0.9	---	17.1 ± 1.0	18.6 ± 1.6
6/10/87	19.1 ± 2.6	14.7 ± 3.8	17.4 ± 3.5	19.4 ± 0.1	15.4 ± 3.3
6/16/87	18.8 ± 4.8	12.6 ± 2.9	13.6 ± 3.8	7.8 ± 4.3	4.0 ± 2.7
			Great Northern (Susceptible)		
6/9/87	18.6 ± 3.0	17.8 ± 4.8	12.0 ± 0.8	16.4 ± 1.5	17.3
6/10/87	17.5 ± 1.8	18.8 ± 2.7	14.3	18.4 ± 1.3	12.7 ± 1.5
6/16/87	18.5 ± 4.0	17.3 ± 1.4	12.0 ± 3.0	12.8 ± 3.8	3.7 ± 4.8
			Pinto		
6/9/87	17.6 ± 1.1	22.1 ± 1.0	16.3 ± 1.0	17.2 ± 1.8	16.6 ± 1.5
6/10/87	16.0 ± 6.5	16.1 ± 1.5	14.1 ± 4.9	16.8 ± 1.1	17.4 ± 2.7
6/16/87	10.0 ± 12.5	11.5 ± 2.9	9.0 ± 2.5	9.8 ± 3.3	8.8 ± 0.7

[a]Mean ± SD for one or two chambers per treatment and one or three plants per cultivar per chamber, for a total of from one to 17 plants per treatment.

Table 34. Effects of Humidity and Ambient Ozone on Transpiration - Treatment Means for Pinto Beans (mg m^{-2} s^{-1})[a]

Date	Treatment				
	Humid Ambient	Humid Filtered	Dry Ambient	Dry Filtered	Dry Outside
6/23/87	6.0 ± 3.5	10.1 ± 3.1	6.4 ± 2.2	6.9 ± 3.9	6.6 ± 3.1
6/24/87	8.3 ± 4.1	11.3 ± 1.6	7.0 ± 1.9	7.7 ± 3.3	8.4 ± 2.2
7/1/87	6.5 ± 3.2	7.7 ± 1.8	5.9 ± 1.6	5.9 ± 1.9	6.1 ± 1.7
7/7/87	7.1 ± 2.8	9.0 ± 1.9	5.8 ± 1.7	6.5 ± 1.5	6.9 ± 2.2

[a]Mean ± SD for three chambers per treatment and three plants per cultivar per chamber.

This again indicated the high sensitivity of stomata to humidity level as observed for tomatoes in the Fall portion of this project, and alfalfa in the previous humidity project (22). Transpiration rates also generally were increased for plants with added humidity; however, the results were statistically significant for only four measurement days each for almonds and beans (Tables 28, 30, 33, and 34).

c. Ozone x Humidity Interactions

There were few statistically significant interactions between ozone and humidity on almonds or beans. For almonds, there were significant interactions for stomatal conductance on 5/12/87 and 6/24/87. For beans, there were significant interaction for both conductance and transpiration on 6/16/87 (Table 28). However, the pattern of response varied for each interaction. For example, almond stomatal conductance was highest for the humid ambient treatment and lowest for the dry ambient treatment on 5/12/87, but highest for the humid filtered treatment and lowest for the dry filtered treatment on 6/10/87. This indicated that the increased gas exchange with added humidity did not result in any consistent increase in sensitivity of the stomata to closure due to ozone.

D. Chamber Effects

There were many statistically significant chamber effects on plant response in this series of studies as shown by comparisons between the dry ambient and outside treatments. All open-top field chambers modify the environment around the plant canopy to some extent, but the modifications are especially great during cooler months such as the fall, winter, and spring (12). These are the same seasons when much of the research in this report was conducted.

1. Injury, Growth, and Yield Effects

There were significant chamber effects for nearly all species (Tables 2, 4, 12, and 20; summarized in Table 35). In the Fall of 1986, the tomatoes in the chambers grew faster than outide plants. At the preliminary harvests, the plants were taller and had more leaf and stem growth in chambers than outside (Table 35). Chamber plants also had more flowers than outside plants. At the final harvest, the tomatoes in the chambers were taller and had higher plant fresh weights and fruit weights

than outside plants. However, the outside plants had actually surpassed the chamber plants in potential productivity by this time, as they had more flowers and small fruit than chamber plants by the end of the study. This difference in chamber response over time may have been in part due to the rapid vegetative growth due to slightly higher temperatures normally found in chambers vs. outside plots in the Fall (14). While this vegetative growth enhanced early fruit production in the chambers, it may have inhibited fruit production later.

The chamber environment enhanced plant growth compared to outside plots for all species grown during the winter months (Table 35). The effects were especially dramatic for wheat and lettuce as seen in previous studies conducted during the same time of the year with these species (15).

The least chamber effect on plant growth was found in the Spring study. This was to be expected as the smallest difference between chamber and outside experiments was found in the warmer months of the year, and the Spring study extended from April into mid-July. No significant differences in growth or yield for chambers vs. outside plots were found for melons, ponderosa pine, or Douglas fir (Table 20). The only significant chamber effect for almonds was a decrease in leaf injury compared to outside plots (Table 35). Beans had mixed chamber effects with some weights increased in chambers and others decreased in chambers compared to outside plots.

2. Physiological Effects

The chamber effect on physiological responses was not as dramatic as the effect on injury, growth, and yield. Tables 6, 17, and 28 indicate the results from statistical analysis for chamber effects for specific physiological responses. The statistically significant chamber effects are summarized in Table 35. Plants had lower physiological process rates in chambers compared to outside plots during the fall and spring months, but higher rates during the winter months.

E. Importance of Humidity in Modifying Plant Response to Air Pollutants

These studies indicated that there is no evidence for an interaction between relative humidity and air pollutants that would result in increased crop losses due to pollutants, especially ozone, in areas with

Table 35. Summary of Statistically Significant Chamber Effects

Study	Species	Response	Effect: Chamber vs. Outside
		Growth, Yield, Injury	
Fall	Tomatoes	Preliminary	
		Height	Chamber plants taller (four harvests)
		Leaf length	Chamber leaves longer
		Lateral length	Chamber laterals longer
		Flower	Chamber more flowers
		Leaf injury	Chamber greater injury
		Stem fresh weight	Chamber greater weight
		Final	
		Injury	Chamber greater injury
		Plant fresh weight	Chamber greater weight
		Flowers	Chamber fewer flowers
		Fruit weight	Chamber greater weight
		Larger fruit	Chamber more fruit
		Small fruit	Chamber fewer fruit
Winter	Wheat	Ear # and weight	Chamber higher
		Height	Chamber plants taller
		Vegetative weight	Chamber greater fresh & dry
Winter	Carrots	Top weight	Chamber greater total & average fresh weights
		Plant weight	Chamber greater total and average fresh weights
Winter	Onions	Fresh weight	Chamber greater total and average weight/plant
Winter	Lettuce	Plant diameter	Chamber greater diameter
		Plant weights	Chamber greater total and head fresh weights
Spring	Almonds	Leaf injury	Chamber less injury

(continued)

Table 35 (concluded) - 2

Study	Species	Effect: ResponseChamber vs. Outside	
Spring	Beans	First Group	
		Bean DW/FW	Chamber higher weight
		Second Group	
		Total bean DW	Chamber higher weight
		DW/bean	Chamber lower weight
		Biomass DW/FW	Chamber lower ratio
		Physiology	
Fall	Tomatoes	Conductance	Chamber lower one date
		Photosynthesis	Chamber lower three dates
		Transpiration	Chamber lower one date
Winter	Lettuce	Transpiration	Chamber higher one date
Spring	Almonds	Conductance	Chamber lower one date
		Transpiration	Chamber lower one date
Spring	Beans	Conductance	Chamber lower one date
		Transpiration	Chamber lower one date

higher relative humidity levels. There was much greater visible injury from ozone with increased humidity, as previously demonstrated in laboratory studies (4,8,17,18). However, this increased injury was not associated with an interaction in terms of commercial yield. Furthermore, there was generally little interaction between humidity and ozone on growth and biomass production. There were many significant effects of either humidity or ozone on plant response, but any increase or decrease in yield, growth, or biomass from one environmental factor usually occurred to a similar extent at both levels of the other factor. This lack of interaction response between ozone and humidity was the same as the lack of interaction response observed between ozone and salinity in previous field studies with alfalfa (12).

To be useful in crop loss assessments, the data for humidity and air pollutant (e.g., ozone) effects would have to be expressed in a multifactorial equation. The form of the equation would be actual yield = maximum yield (y intercept) - (humidity level x slope for humidity response) - (ozone concentration x slope for ozone response) - (interactions). If the analysis of variance indicated a significant humidity x ozone interaction, then the interaction loss term could be quite large, substantially modifying and overshadowing the individual ozone or humidity effects on yield. However, as this study documented, there are no significant interactions between ozone and humidity on yield of the crops studied: tomatoes, beans, and melons. Therefore, only the humidity and ozone single effects would be considered.

Both humidity by itself and ozone apparently reduced yields for tomatoes and beans. The effect of humidity itself on crop yield in the field has not been studied directly in air pollution studies. However, humidity effects are indirectly suggested by the overall lower tomato yields for 1982 compared to 1981 at Livermore (20). The lower yield in 1982 was associated with cooler increased humidity and lower air temperatures in 1982 than in 1981 due to "El Nino" conditions. The increased humidity in 1982 likely resulted in less flower pollination (6) and hence less fruit production than in 1981.

However, since only ozone is of direct interest from a control perpective, knowledge of the effect due to humidity itself is not of great importance. Inclusion of only the ozone effect portion of the equation would still indicate the relative effect of different ozone standard scenarios compared to ambient concentrations regardless of the actual crop yield as affected by humidity.

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